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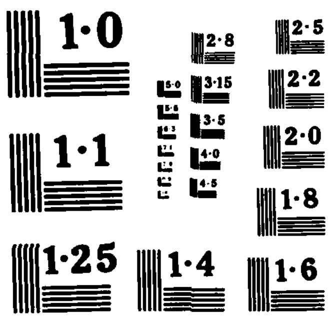
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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

DESIGN OF A VELOCITY AND POSITION CONTROL
LABORATORY SERVO SYSTEM

by

Michael A. Ziegler

September 1987

Thesis Advisor George Thaler

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Design of a Velocity and Position Control Laboratory Servo System

by

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Lieutenant, United States Navy
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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

In support of a course in automatic control theory, a velocity and position control laboratory servo system was designed for use in laboratory exercises. The system is constructed using a commercially available DC motor and power amplifier, which are interfaced to a student control panel. All system changes and measurements are conducted with the control panel. The system can be operated open or closed loop, in a position or velocity control mode, and has several adjustable compensators incorporated in the signal paths. This thesis provides detailed construction, wiring, and system testing steps, along with the required scale drawings, necessary to perform the hardware integration. A set of laboratory procedures, example laboratory reports, and advanced servo control problems are included for instructional purposes.

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I. INTRODUCTION

A. BACKGROUND

Many instructors will agree that one of the most effective means of transferring knowledge to students is through the use of laboratory exercises with hands-on equipment experimentation. A difficult task for an instructor is to locate a commercial product which is safe, easy to operate, instructive for students, and meets the needs of the course.

A requirement for a servo motor laboratory system arises in a basic electrical engineering course in automatic control systems. The servo motor system is useful in demonstrating the response of open and closed loop control systems, both in speed and position regulation. Such a system may also be used to demonstrate system identification, cascade and feedback compensation of control systems using analog and/or digital signals, mechanical resonances, the effects of external loads to the system, and many more control system principles.

B. SYSTEM SPECIFICATIONS

The servo motor system in current use at the school has proven to be difficult for students to operate. This system has developed into a collection of purchased and facility designed components which are not completely compatible. In the conduct of experiments, problems arise in areas such as dead zone and saturation nonlinearities, limited system bandwidth, complicated component connection for students, and difficulty in obtaining reproducible results.

The problems mentioned above justified the need for a replacement servo motor laboratory system. The system to be designed, must have limited nonlinearities, greater bandwidth, minimal component interconnection to be performed by the student, and give reproducible results. Additional design criteria are given in Table 1.

TABLE 1

SYSTEM DESIGN SPECIFICATIONS

Criteria	Specification
Closed loop bandwidth (velocity mode)	> 50 Hz
System response	linear
System components	compatible and stable
Current/voltage limiting	internal to components, adjustable
Operability	simple to operate and maintain
Adaptability	capable of modification

II. PRELIMINARY DESIGN

The basic components required of the servo motor laboratory system are a permanent magnet DC motor with integral tachometer and a linear preamplifier/power amplifier to drive the motor and accept command and feedback signal inputs. The choice of components is based on their ability to meet the criteria of Table 1, and their affordability and availability. The bandwidth, which can be attained by the new system, will be based primarily on the DC motor characteristics. A model of a DC motor is needed to determine the bandwidth possible using parameter values available from suppliers.

A. DC MOTOR EQUATIONS AND TRANSFER FUNCTION

Modelling of a DC motor is broken down into two equations, the electrical and dynamic or mechanical equations.

1. Electrical Equation

The equivalent electrical circuit of a D.C. motor armature is shown in Figure 2.1. Let the motor voltage and current be V and I_a,

respectively. The relation between these variables is given by equation 2.1. Here, L_a is the armature inductance of the motor, R is the motor resistance, and E_g is the internally generated counter emf.

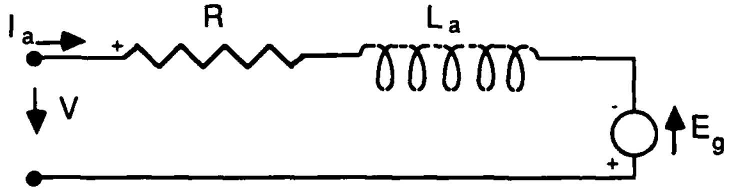


Figure 2.1. Equivalent Electrical Circuit of DC Motor

$$V = L_a \frac{dI_a}{dt} + RI_a + E_g \tag{2.1}$$

The internally generated emf, E_g, is usually considered proportional to the motor's angular velocity, ω.

$$E_g = K_E \omega \tag{2.2}$$

The equations above can be combined to form equation 2.3, which is known as the *electrical equation of the motor.* [Ref. 1:p. 2-17]

$$V = L_a \frac{dI_a}{dt} + RI_a + K_E \omega \tag{2.3}$$

2. Dynamic Equation

The dynamic equation of a motor models the mechanical properties. Figure 2.2 is a schematic model of a motor with the associated forces acting upon it.

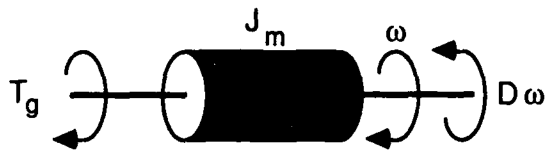


Figure 2.2 Schematic Model of a DC Motor

In Figure 2.2, ω is the angular velocity, D is a constant which takes into account all viscous friction effects which are proportional to ω. The constant friction torque effects in the motor were assumed to be negligible. T_g is the drive torque and for a permanent magnet DC motor, the drive torque is proportional to the armature current I_a.

$$T_g = K_T I_a \tag{2.4}$$

The relation between drive torque and velocity is determined by the torque equilibrium equation, called the *dynamic equation* of the motor, where J_m is the moment of inertia of the motor armature.

$$T_g = J_m \frac{d\omega}{dt} + D\omega \tag{2.5}$$

3. Motor Transfer Function

The response of a motor in a system can be described by a transfer function between the motor voltage and angular velocity. By taking the Laplace transformation of the motor equations, we obtain:

$$V(s) = (sL_a + R)\, I_a(s) + K_E\omega(s) \qquad (2.6)$$

$$T_g(s) = K_T I_a(s) \qquad (2.7)$$

$$T_g(s) = J_m s\omega(s) + D\omega(s) \qquad (2.8)$$

The corresponding transfer function is:

$$G_m(s) = \frac{\omega(s)}{V(s)}$$

$$= \frac{K_T}{(sL_a + R)(sJ_m + D) + K_E K_T} \qquad (2.9)$$

The transfer function model can be used to generate the frequency response of the motor and determine the system bandwidth. Equation 2.9 can also be expressed in terms of mechanical and electrical time constants, since in practice, the roots of the denominator of G_m are negative and real. Therefore, it may be written as equation 2.10 [Ref. 1:p. 2-18], where, τ_E is the

electrical time constant and τ_m is the mechanical time constant in seconds. The values of these constants are more frequently available in suppliers catalogues and are more accurate than the lumped parameter values of R, L_a, J_m, etc..

$$G_m(s) = \frac{1 / K_E}{(s\tau_E + 1)(s\tau_m + 1)} \tag{2.10}$$

4. Tachometer Equation

A tachometer is required to convert ω from rad/sec to a voltage level which can be used for feedback in a speed control system. A tachometer which is integral to the motor is more desirable in this system because of fewer complications with couplings or alignment. The output voltage of an ideal tachometer is proportional to the angular velocity ω, equation 2.11.

$$V_g = K_g\omega \tag{2.11}$$

In practice, the voltage will have other components, which appear as a ripple voltage in the tachometer output. These can normally be reduced by passive element filtering of the tachometer output and proper shielding.

B. AMPLIFIER CHARACTERISTICS

Some type of amplifier is required in the servo system to accept a command signal and drive the motor accordingly. The features which are desirable in the amplifier are:

Compatible with DC motor
Sufficient bandwidth > 1 kHz
Internal AC to DC power supply
Can accept command and feedback signals
Over current/voltage protection for motor and amplifier
Easy to modify for interfacing to student control panel
Small in size and weight
All internal signals accessible
Adjustable gain
Linear response

An amplifier can be modelled in the transfer function form as an adjustable gain low pass filter, equation 2.12 [Ref. 1:p. 4-16],

$$G_a(s) = \frac{V_{out}(s)}{V_{in}(s)} = \frac{A}{s\tau_a + 1} \qquad (2.12)$$

where A is the amplifier gain and τ_a is the time constant of the amplifier. The bandwidth of an amplifier depends on the gain. Gain and bandwidth are normally specified together as a gain bandwidth product. The value of τ_a will therefore depend on the gain used in the amplifier.

C. MOTOR SPEED CONTROL

The transfer functions derived to this point, can be used to build a block diagram model of a motor speed control system using velocity feedback. Figure 2.3 is the speed control block diagram where V_c is the commanded velocity (a voltage input), ω_o is the output velocity (in radians/sec), and k is a velocity scaling constant in the tachometer feedback channel.

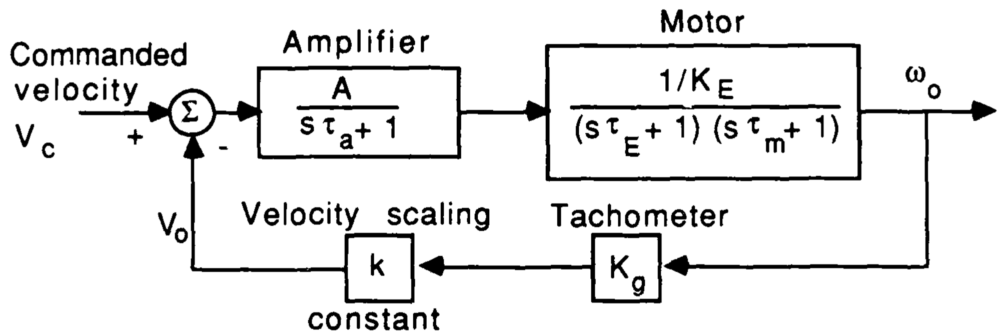


Figure 2.3 Block Diagram of Motor Speed Control

We can determine the closed loop transfer function by block diagram manipulation. Since we do not normally wish to measure ω_o directly, we instead use the signal V_o as our output. This places the K_g and k blocks into the forward path of the system. The equation for the forward path is:

$$G_{eq}(s) = G_a(s)G_m(s)kK_g = \left[\frac{A}{s\tau_a + 1}\right]\left[\frac{1/K_E}{(s\tau_E + 1)(s\tau_m + 1)}\right]kK_g \quad (2.13)$$

The closed loop transfer function is found from:

$$\frac{V_o(s)}{V_c(s)} = \frac{G_{eq}(s)}{1 + G_{eq}(s)} = G_{cl}(s) \qquad (2.14)$$

Thus the complete closed loop transfer function is:

$$G_{cl}(s) = \frac{kK_g A / K_E}{(s\tau_a + 1)(s\tau_E + 1)(s\tau_m + 1) + kK_g A / K_E} \qquad (2.15)$$

The closed loop bandwidth is determined by calculating the frequency at which the magnitude of $G_{cl}(s = j\omega)$ has been reduced by 3 db from its DC value at $\omega = 0.0$. This is most easily done by using a computer program to plot the frequency response of $G_{cl}(s)$.

D. COMPONENT SELECTION

A search of suppliers' catalogues was conducted to locate system components which would meet the criteria for the amplifier and Table 1. As a result, two suitable systems were found from the same manufacturer.

1. MCSL System

The first system is an integrated servo motor control system laboratory, the Electro-Craft Motomatic Control System Laboratory, or MCSL, part no. 9042-0050. [Ref. 2:p. 26] This system consists of

an electronic control chassis, which is used to power and compensate the servo motor, an electro-mechanical chassis, which supports the servo motor, position potentiometer, and speed reduction unit, and an instrumentation chassis, which houses meters for measuring motor speed and current, and a voltmeter for other signals. The purchase of the system also includes a laboratory manual which contains descriptions of the equipment and laboratory experiments that can be carried out on the system.

System parameters made available by Electro-Craft, indicated this system would have the desired bandwidth. However, because of its integrated nature, it would be difficult to make modifications to the system. One of these systems was purchased by the Naval Postgraduate School, and it was used to make comparisons with the designed system.

2. Designed System

The components incorporated into the servo motor laboratory system were an LA-5600 Linear Amplifier with notch filter (part no. 9080-0555) and a compatible E588 permanent magnet D.C. motor with an integral tachometer (part no. 0588-33-500). Tables 2 and 3

list the major technical specifications given in the catalogue, [Ref. 2:pp. 28-30].

TABLE 2

LA-5600 FEATURES

Performance Characteristic	Value
Open Loop DC Gain (A/V)	1200
Bandwidth (Hz)	DC-2000
RMS Output Current (A)	9

Interface Signals	Input (I)/Output(O)
Velocity Command Signal (VCS)	(I) analog
Auxiliary Input Signal (AUX)	(I) analog
Forward Amplifier Clamp (FAC)	(I) digital
Reverse Amplifier Clamp (RAC)	(I) digital
Motor Hold Clamp (MHC)	(I) digital
Amplifier Inhibit Clamp (INH)	(I) digital
Motor Velocity Output (MVO)	(O) analog
Motor Current Output (MCO)	(O) analog
System Status Output (SSO)	(O) digital

TABLE 3

E588 DC MOTOR FEATURES

Performance Characteristics	Value
Continuous Stall Torque (oz-in) (@ 155°C Armature Temp.)	50
KT Torque Constant (oz-in/amp)	11.8
KE Voltage Constant (V/krpm)	8.7
Electrical Time Constant (msec)	2.3
Mechanical Time Constant (msec)	11.3
Tachometer Voltage Constant (V/krpm)	14.2
Tachometer Ripple [pk to pk at 500 rpm](%)	5

The amplifier's electronics, a printed circuit board mounted above the AC power conditioning circuits, are easily accessible for modifications and interfacing. The LA-5600 amplifier has an internally adjustable current limit, adjustable servo compensation circuits, AC to DC power supply, and an adjustable notch filter circuit. The amplifier can be setup for velocity and position feedback or constant current (motor torque) feedback modes.

The envisioned system is to consist of an equipment track similar to the MCSL system, which will support the DC motor and position potentiometer and the LA-5600 amplifier mounted adjacent to a student's control and signal interface panel.

E. COMPONENT JUSTIFICATION

A simulation study of the system components was carried out prior to purchasing the motor and amplifier. Using the motor and amplifier models previously developed, Figure 2.3 and equation 2.15, a computer model can be generated to determine the frequency response of the system. This simulation model will give system bandwidth based upon the supplier's numerical data.

1. Velocity Control Frequency Response Simulation

The required motor and amplifier constants, Tables 2 and 3, were converted to standard MKS units, with the following results:

Motor Constants

$K_E = 8.308 \times 10^{-2}$ volts/rad/sec
$K_g = 0.1356$ volts/rad/sec
$\tau_E = 2.3 \times 10^{-3}$ sec
$\tau_m = 11.3 \times 10^{-3}$ sec

Amplifier Constants

$\tau_a = 1/(2\pi f)$ where f = (open loop gain x bandwidth)/A
amplifier bandwidth is a function of the gain used
A = variable gain

The constants were incorporated into the frequency response equations and simulated using a *DSL/VS simulation language* available at NPGS [Ref. 3]. The DSL program used to obtain the frequency response is enclosed in Appendix A, Figure A.1.

Figure 2.4 is the closed loop frequency response of the system in the velocity control mode, with an amplifier gain of 20. The scaling factor k was chosen to give a velocity scaling of 1 volt/500 rpm. As the figure indicates the system bandwidth (-3db) occurs at 560 rad/sec or about 90 Hz. This meets our criteria and can be increased by raising the gain.

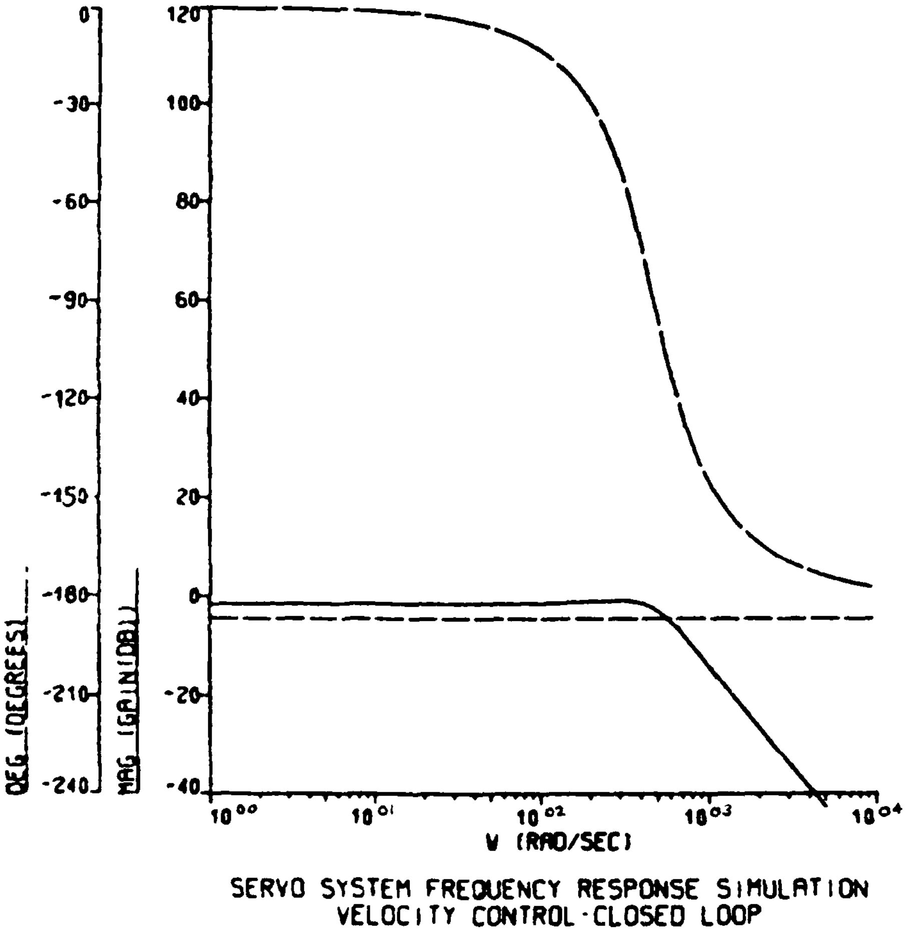


Figure 2.4 System Frequency Response Simulation
Velocity Control - Closed Loop

2. Position Control Frequency Response Simulation

The position control mode block diagram of the system is shown in Figure 2.5. The integrator relates θ to ω, where θ_o is the output shaft angular position. The tachometer feedback is removed in order to examine the position system response without damping. The simulation program is given in Figure A.2.

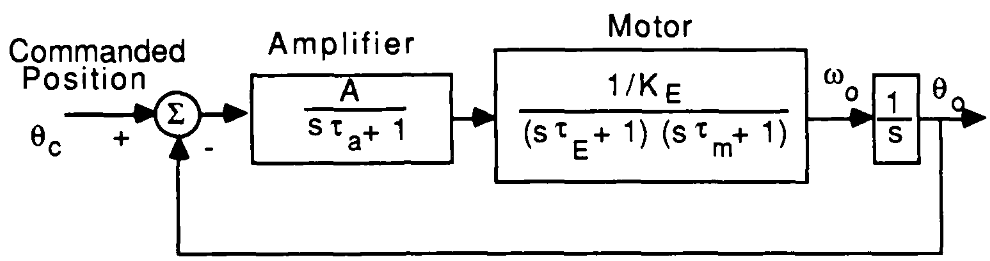


Figure 2.5 Block Diagram of Motor Position Control

Figure 2.6 is the frequency response plot for position control. The system bandwidth is found to be 95 rad/sec or about 15 Hz. This bandwidth is sufficient in the position control mode and can be increased by raising the gain or adding velocity feedback damping.

3. System Design Conclusions

The proposed components will meet the criteria of Table 1 and the desired amplifier features. The procurement cost for the motor and amplifier is under $1000.00, which is less than half the cost of the Motomatic Control System Laboratory.

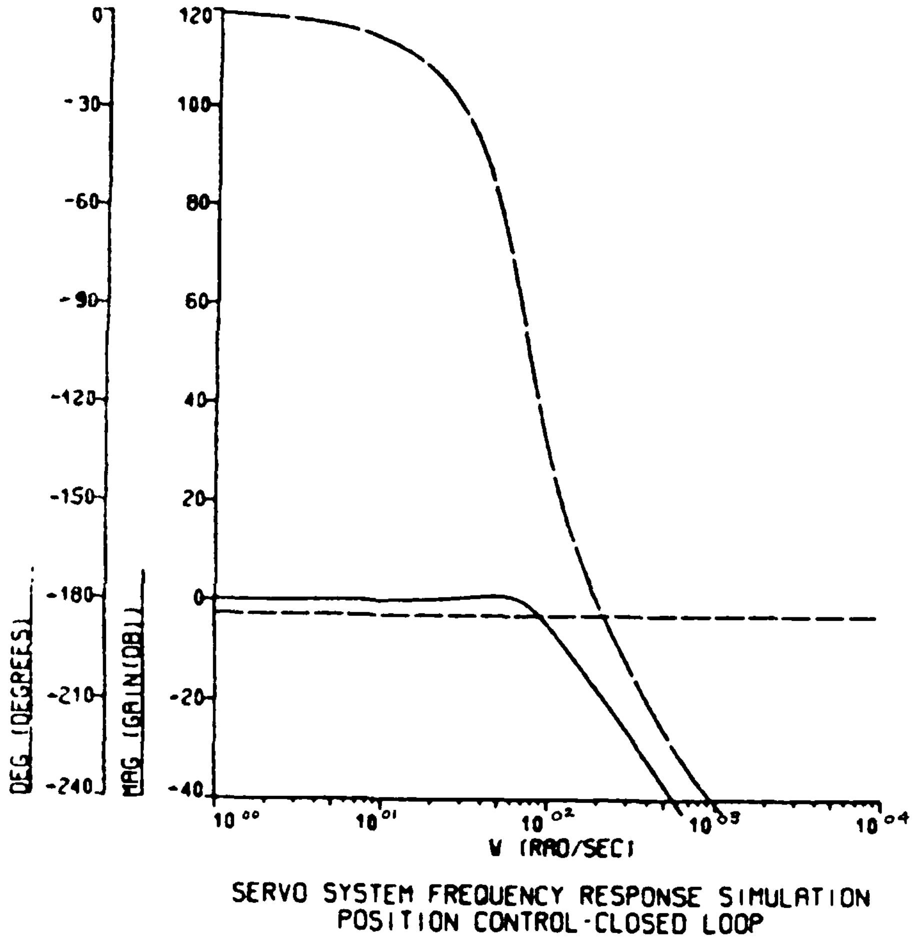


Figure 2.6 System Frequency Response Simulation
Position Control - Closed Loop

III. SYSTEM IMPLEMENTATION

A. GENERAL SYSTEM LAYOUT DESIGN

The system layout is designed to solve the problems of complex component interconnections, compatability, and ease of operation. This is accomplished by providing the student with a self-contained control panel where all component interfacing, control, compensation adjustment, and signal testing occurs. The amplifier has the actual control and compensation circuits, however the student need only manipulate switches and potentiometers on the control panel to make changes in the system.

1. Amplifier Block Diagram

A detailed circuit diagram of the amplifier is required to determine the possible interconnections between the control panel and amplifier. This will determine the control functions of the panel. Figure 3.1 depicts the circuitry in a basic block diagram form. This generalized diagram is necessary for proprietary reasons. The manufacturer will supply a detailed circuit diagram upon request.

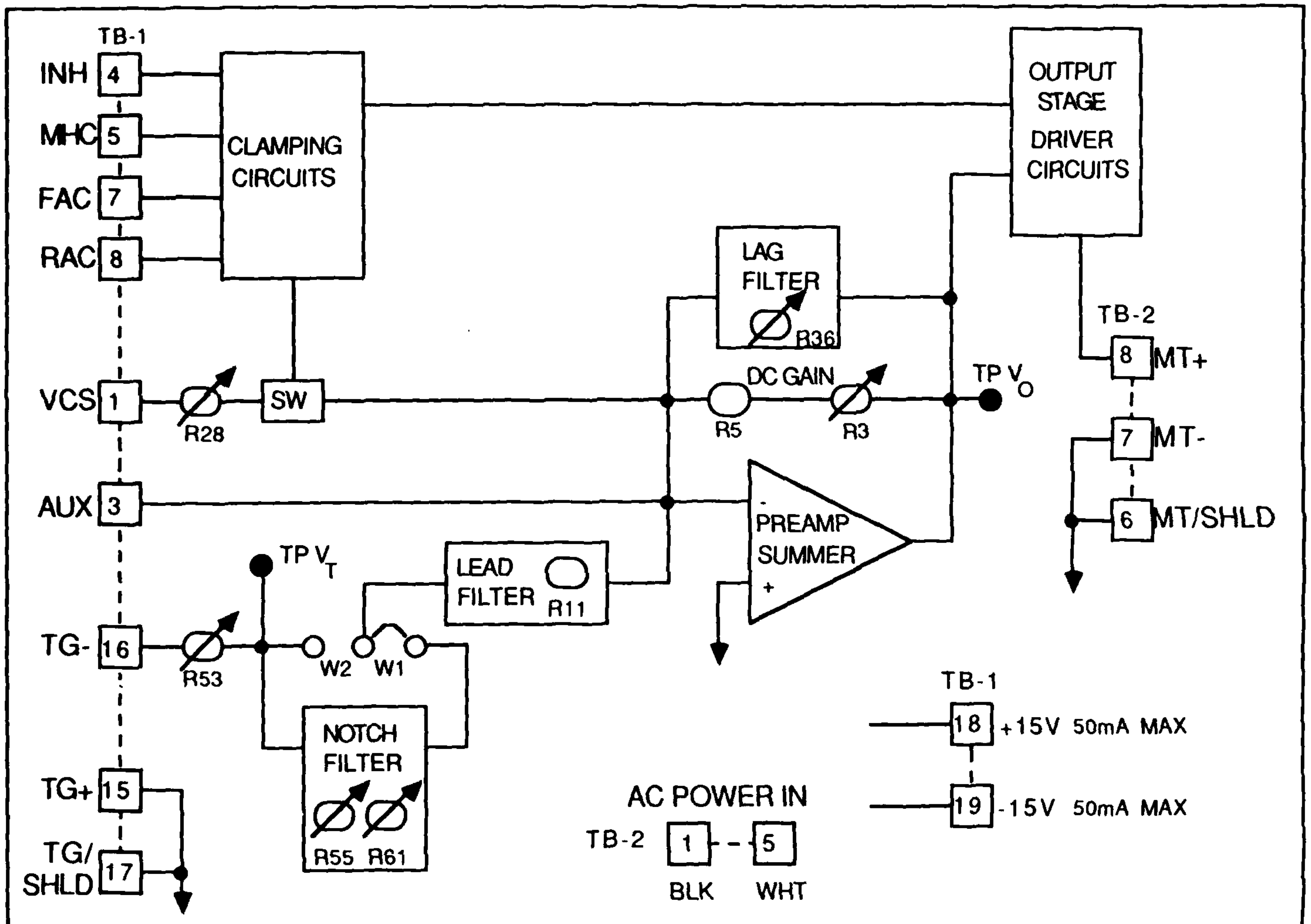


Figure 3.1 LA-5600 Amplifier Basic Block Diagram

The instruction manual for the LA-5600 amplifier [Ref. 4] contains a description of all the terminals on the amplifier. Table 4 contains a description of the terminal connections and other codes used in Figure 3.1. The numbers correspond to the terminal block connection points. Resistors are labeled by numbers which correspond to the detailed circuit diagrams of the amplifier (i.e., R5, R36, etc.). Variable resistors (potentiometers) are indicated with an arrow through their symbol.

TABLE 4

AMPLIFIER TERMINAL DESCRIPTIONS

Terminal/Name	Function
INH Inhibit	Inhibits the output drivers
MHC Motor Hold Clamp	Open circuits VCS
FAC Forward Clamp	Inhibits the forward CCW output driver
RAC Reverse Clamp	Inhibits the reverse CW output driver
VCS Velocity Command Signal	Velocity command input voltage point, R28 is used for scaling
AUX Auxiliary Input	Additional input to summing amplifier
TG- Tach Input -	Input from negative lead of tachometer
TG+ Tach Input +	Input from positive tachometer lead
TG/SHLD Tach shield	TG- lead shielding cable
MT+ Motor Terminal +	Positive output to motor
MT- Motor Terminal -	Negative motor lead connection point
+15V	Regulated +15 volt output
-15V	Regulated -15 volt output
TB-1	Terminal block 1
TB-2	Terminal block 2

2. System Control Features

The control features, which can be incorporated into the control panel, are based on the capability of interfacing with the amplifier. Examining Figure 3.1 the following control features may be incorporated in the student control panel:

Individual control of clamping inputs INH,MHC,FAC, and RAC
Command voltage signal input to VCS
Position feedback signal to AUX through a switch
Velocity feedback signal at TG- and TG+ through a switch and scaling potentiometer
Ability to switch notch filter in or out of system, and adjust
Ability to switch lead filter or add user filter
Ability to switch lag filter in or out of system and adjust or add user filter
Adjust DC gain
Provide terminals for cascade compensation or digital sampling in the forward path after the gain amplifier with scaling adjustment.
Provide +15V and -15V power

These control panel features can be implemented with minimal modification to the amplifier circuit layout. These features are arranged in a signal flow schematic, Figure 3.2. All switches, potentiometers, and test points will be located physically in their indicated locations. The abbreviations used in Figure 3.2 are for test, switch, and potentiometer positions; T1 = test point no. 1, SW1 = switch no. 1, and P1 = potentiometer no. 1.

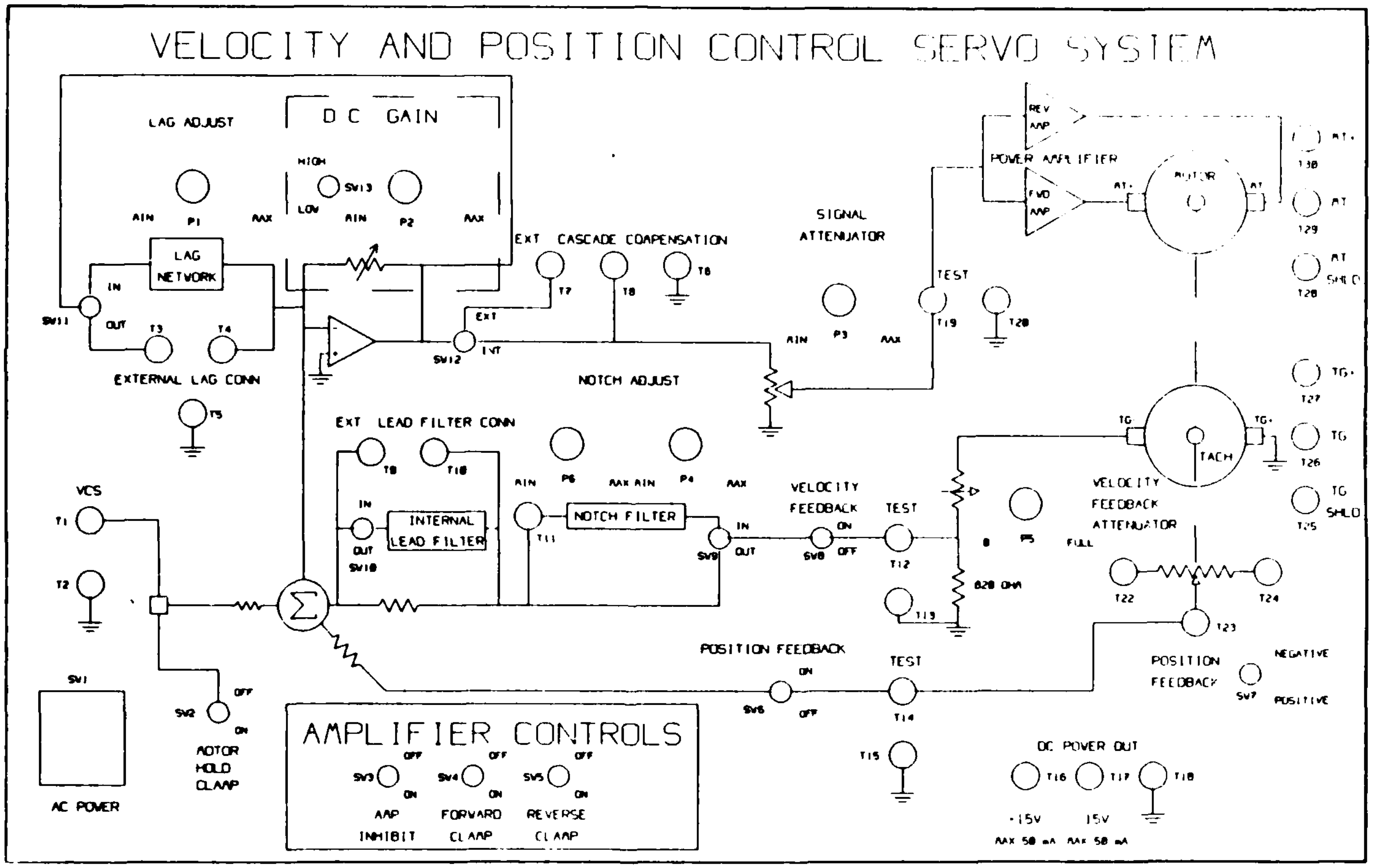


Figure 3.2 Signal Flow Schematic of the Velocity and Position Control System

3. Component Integration

An overall system layout must include the physical hardware positioning. General descriptions and layout justifications follow, specific construction details are given in later sections.

a. DC Motor

The DC motor with integral tachometer and the position potentiometer must remain aligned during operation in a position control mode and they should be uncoupled during a velocity control mode. This can be accomplished by mounting the motor and position sensor on separate sleds, which can be slid along an alignment track.

b. Control Panel and Amplifier

The interface between the control panel and amplifier will require numerous connections. To eliminate cabling problems, the amplifier and control panel are physically attached. Control panel size was based on the number of connections and devices required; final size is 16" x 10". Careful positioning of the amplifier is required to ensure adequate cooling of circuit components by the installed fan. Figure 3.3 shows a top view of the physical layout of the Velocity and Position Control System at about 1/8 th scale.

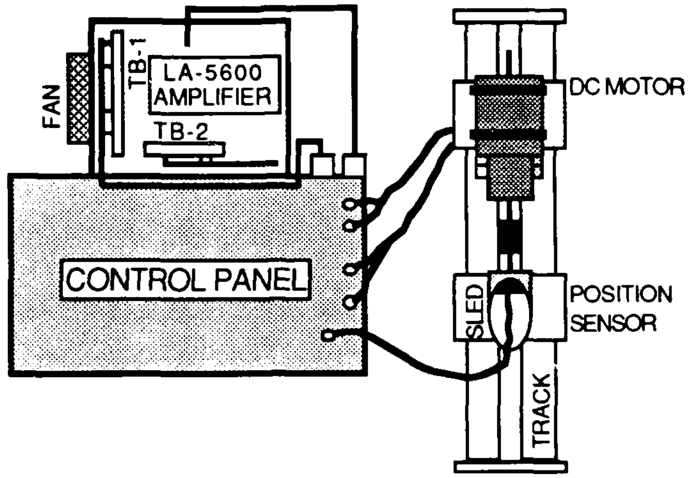


Figure 3.3 Top View of System Physical Layout

B. EQUIPMENT TRACK CONSTRUCTION

The equipment track and its associated parts are designed to support the servo motor, position potentiometer, and other external devices (i.e. external loads, speed reduction units, etc.). Materials are indicated on the drawings referenced in the following sections.

1. Track Base

The Track Base, Figure B.1 (Appendix B), supports and aids in alignment of the motor and coupied devices. P:eces "B" are held in place by set screws in pieces "A". It should be placed on a flat surface to tighten the set screws and ensure correct alignment.

2. Equipment Sled

The motor and Position Potentiometer Support are physically mounted on an Equipment Sled, Figure B.2. The parts needed to complete the sled are shown in Figure B.3. A minimum of two sleds are required. The Lower Sled Support is attached to the underside of the sled at point "A". The Sled Clamp Bracket is held in place by a 1/4-20 bolt, with a plastic thumb-wheel mounted on the head. The bolt passes through the Clamp Bolt Sleeve, then the Equipment Sled at point "B", and is screwed into the Sled Clamp Bracket.

3. Motor Mounting and Wiring

Mounting holes for the motor are not indicated on the sled diagram. The motor can be mounted by cutting two pieces of sheet metal about 1/2" wide and 6" long, and forming brackets over the motor housing, then drill and tap holes in the sled to secure. Figure 3.3 shows the proper motor orientation for mounting.

Once the motor is mounted on the sled, the wiring can be performed as follows:

Cut one piece of 18 AWG insulated wire the same length as the motor leads.

Crimp and solder a forked tongue terminal on the end of the wire and connect this terminal to the motor housing with the existing screw in the motor housing underside.

Stuff these wires, (MT/SHLD), black (MT-) wire and red (MT+) through an 18" length of 1/4" diameter PVC tubing.
Connect red, black, and blue male banana plugs to the ends of the red, black, and shield wires, respectively.
Shield the green tachometer (TG-) wire by cutting a 24" length of coaxial cable, bare the center conductor on both ends, solder the end of the green wire to the center conductor and pull the center conductor and insulation out, thus replacing it with the green wire.
Stuff the white tachometer wire and the shielded green wire through a 18" piece of 7/16" PVC tubing.
Make an incision in the shielding about 2" from the end and pull the green wire out through this hole.
Strip the outer insulation on the shielding and twist solid.
Connect yellow, green, and blue male banana plugs to the white, green, and shielding wires respectively.
Clamp the two wire bundles to the underside of the sled using two 1/2" nylon clamps attached with the screws used for the Lower Support Bracket.

4. Potentiometer Mounting and Wiring

The Position Potentiometer Support, Figure B.4, is mounted by drilling holes at point "A" of the sled, inside of the Lower Sled Support holes, countersinking, then drilling and tapping holes in the Potentiometer Support to match. Secure with bolts from beneath the sled, then reinstall the Lower Sled Support. A 5 kΩ single turn, 360° continuous travel, potentiometer is mounted in the Support, see Figure 3.3. Three 18 AWG wires cut 18" in length and stuffed in 1/4" PVC tubing are used to wire the potentiometer. Mount a green,

yellow and red male banana plug on the end of a wire. The other ends are soldered to the potentiometer terminals as follows: yellow plug wire to the slider contact (pin 2), green plug wire to pin 1, and red plug wire to pin 3. Install a nylon clamp around the wire bundle and bolt it in place using one of the support mounting bolts.

5. Motor Coupling

The top of Figure B.4 shows the Shaft Coupling and Coupling Connector for the motor and potentiometer. Two Shaft Couplings and one Coupling Connector should be made. The Shaft Couplings are connected to the motor and potentiometer shafts with set screws. The Coupling Connector is designed to allow the motor and potentiometer to be uncoupled by sliding them apart on the Equipment Track.

C. CONTROL PANEL CONSTRUCTION

The control panel is constructed to deliver the best representation of the system to the student, ensuring safety and ease of operation. The basic material chosen for the control panel is Lexan, a polycarbon material, with strength characteristics better than acrylics. This material can be bent in shapes without heating.

The control panel is divided into six pieces: two top panels, the left and right side panels, and front and back panels.

1. Top Panels

Two top panels are required, one of 1/8" Lexan and one of 1/8" aluminum. Figure B.5 shows the top panel dimensions. The aluminum panel provides rigidity to the top of the control panel. A full scale drawing of the system signal flow schematic, Figure B.6, is placed over the aluminum panel and the Lexan panel is placed over both. In this manner the Lexan serves to protect the schematic from wear and tear.

2. Side Panels

The right and left side panels are shown in Figures B.7 and B.8 respectively. Front and back panels are shown in Figure B.9, with additional modifications for the back panel in Figure B.10. When drilling the assembly screw holes, ensure proper alignment of the pieces. Holes should be drilled about one inch deep for tapping.

3. Side Panel Assembly

Screws used in assembly of the side panels are 1 1/4" 6-32 phillips flat heads and should be countersunk flush with the panels.

Two 15 pin D-type cable connectors, one female (slot A) and one male (slot B), are mounted in slots A and B of the back panel from the outside with 4-40 jacksocket screws.

4. Top Panel Addition

Mounting holes in the top panels and into the side panels should be drilled simultaneously, after side panel assembly.

Switch, potentiometer, and test connection positions in Figure B.6 are indicated by a circle. Using a full scale reproduction of Figure B.6, carefully cutout these circles. Insert the schematic between the two top panels and install in the side panel assembly.

5. Control Panel Component Mounting

All circuit components in the control panel top must have a threaded mounting shaft which is a minimum of 5/16 of an inch in length. The type and quantity of components required for the control panel circuitry are listed in Table 5. Similar items of suitable dimensions can be substituted for any of the components. The components listed in Table 5 were used in the first servo system construction. Table 5 indicates the position of each type of component by referencing the positions shown in Figure B.6.

TABLE 5

CONTROL PANEL CIRCUIT COMPONENTS

Name	Description	Quantity
Toggle Switch	Submini size, black handle covers, solder connections, 1/4" mounting hole, rated for 5 amps, 115 VAC, SPDT, both positions on. Positions - SW2,3,4,5,6,8,10,11,12,13.	10
Toggle Switch	Same as above except, DPDT. Positions - SW7 and SW9	2
Rocker Switch	Square snap in place mount, 7/8" x 1" mounting hole, DPDT with ON/OFF indicator, quick-connect terminals, 10 amp, 250VAC. Position - SW1	1
Potentiometers	Large single turn pots, 3/8" mounting hole, solder terminals, 1 amp, values follow:	
	10 kΩ at positions P2,3,4,5,6.	5
	2 MΩ at position P1	1
Female Plugs	Banana plug female receptacles, bolted in type, quick-connect/solder terminals, in the following colors:	
	Black at positions - T2,5,6,13,15,18,20,29	8
	Red at positions - T1,16,22,30	4
	Green at positions - T17,24,26,33	4
	Blue at positions - T11,12,14,19,25,28,31	7
	Yellow at positions - T3,4,7,8,9,10,23,27,32	8

The mounting holes for components should be drilled with the control panel assembled to ensure proper alignment with both top panels and the schematic. Mill out or drill and hand saw the slot to mount the rocker switch. Mount components from Table 5 in the top panel, with all switch terminals in a line parallel to the side panels.

6. Control Panel Wiring

The wiring used in the control panel is 22 AWG Teflon insulated or a suitable substitute. Connections to female banana plug terminals and the AC Power (SW1) rocker switch are made with "fingrip or push-on" connectors, crimped and soldered to the wires. All other wires are soldered to terminals.

a. AC Power Cord

A 48" length of three conductor AC power cord with a three prong plug should be inserted through Hole 1 of the back panel, see Figure B.10. Crimp and solder push-on connectors to the white (neutral) and black (hot) wires. Crimp a splice connector on the green (ground) wire. Insert a 36" length of AC power type cord (no plug) through Hole 2 of the back panel. Crimp and solder push-on connectors to the green and white wires, and crimp the green wire into the other end of the splice from the AC power cord. Refer to Figure 3.4 and connect the wires to the AC Power switch SW1.

b. Toggle Switches and Potentiometers

The routing of wiring for all switches and potentiometers is shown in Figures 3.4 and 3.5.

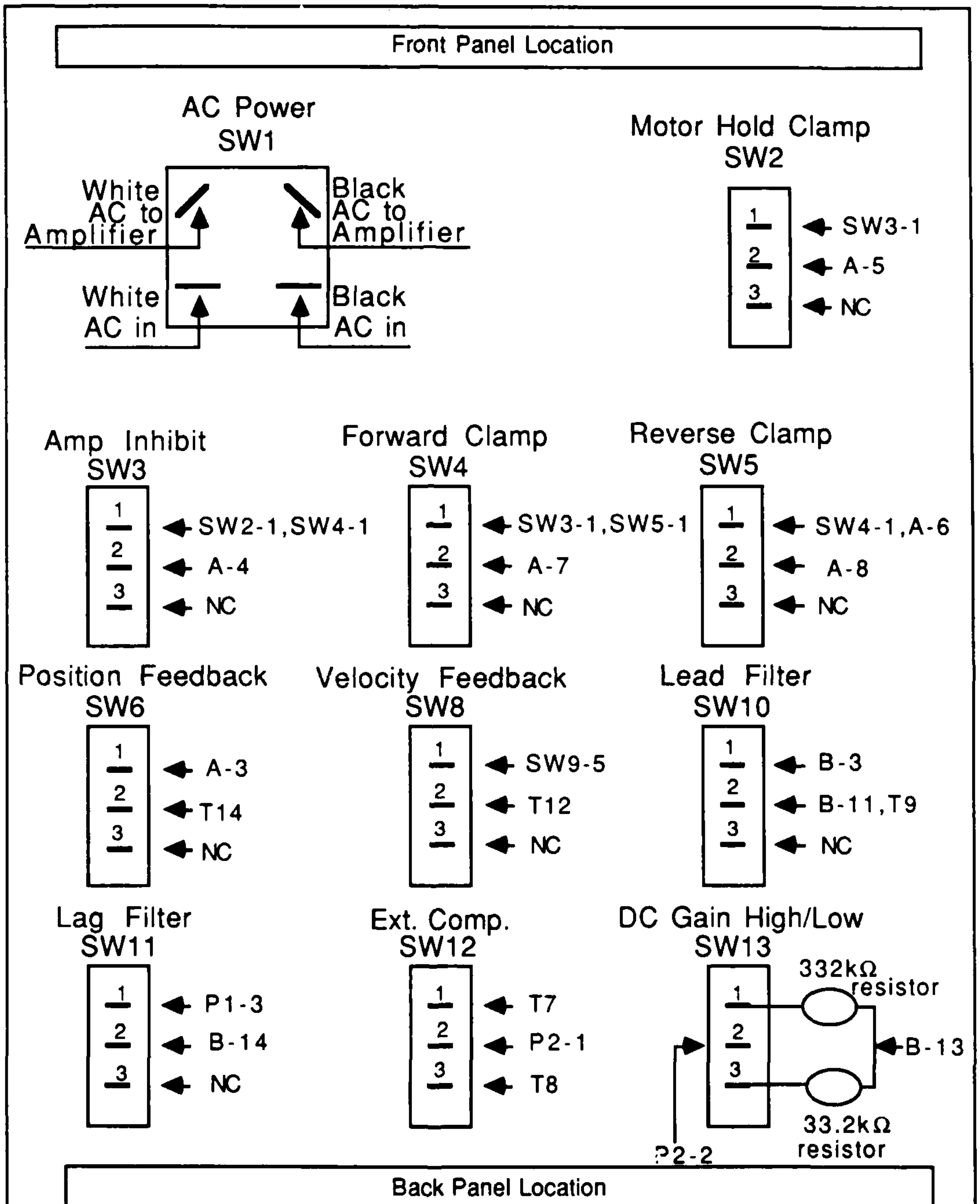


Figure 3.4 Switch Wiring Diagrams
(Underside View of Control Panel)

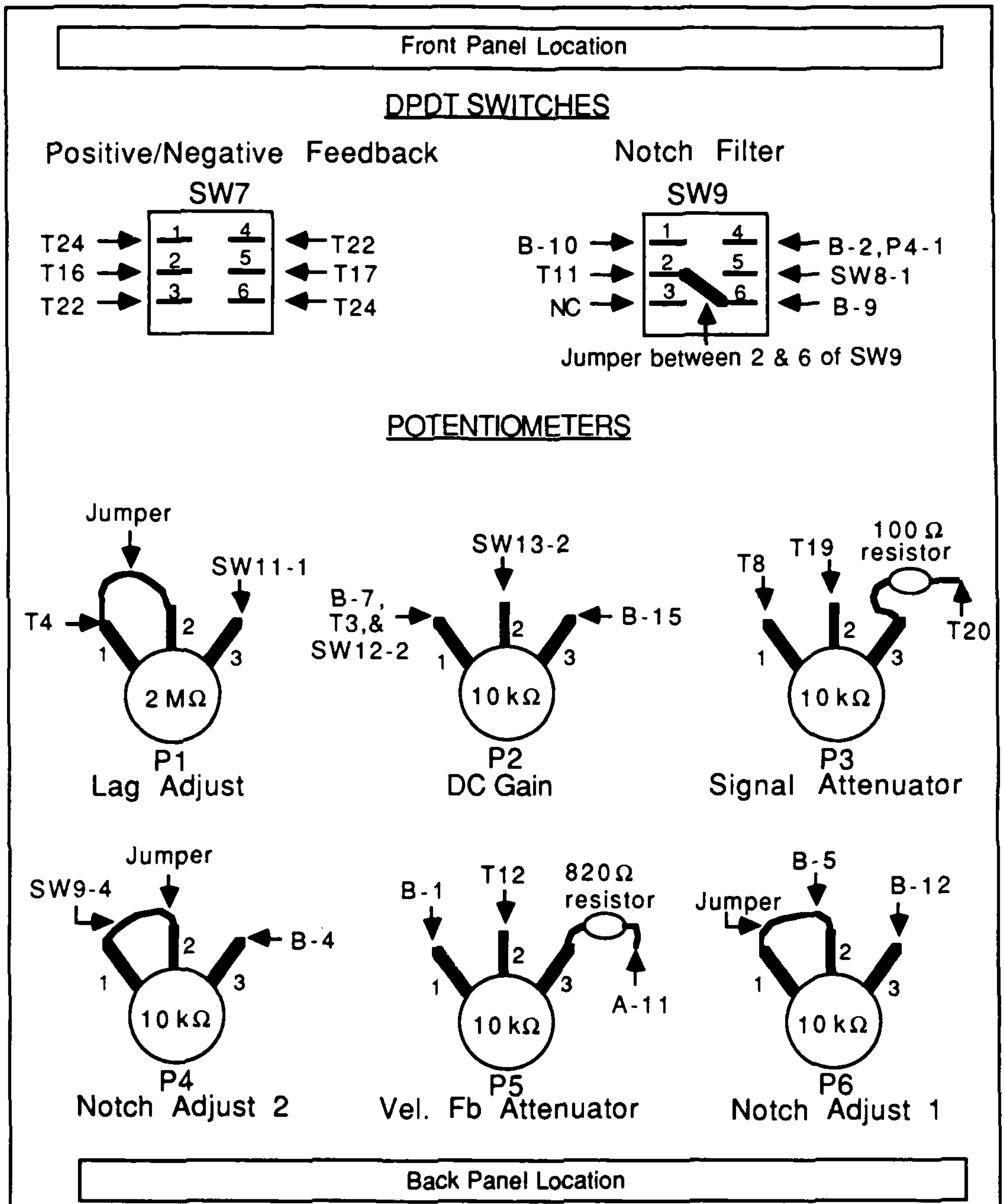


Figure 3.5 Switch and Potentiometer Wiring Diagrams
(Underside View of Control Panel)

All connections are solder joined, except the AC Power switch. Figures 3.4 and 3.5 show all switches in the proper orientation with respect to the front and back panels, when the control panel is viewed from the underside. Mount adjusting knobs on all potentiometers, and rotate fully counterclockwise, then adjust so that the control knob points to the minimum position on the schematic. The codes used in Figures 3.4 and 3.5 match those used in Figure B.6, other codes having the following meanings:

SW3-1	=>	Switch SW3, terminal no. 1 (toward front panel)
A-5	=>	D-connector slot A, pin 5
B-3	=>	D-connector slot B, pin 3
T14	=>	Banana plug terminal T14
P1-3	=>	Potentiometer P1, terminal no. 3 (far right)
Jumper	=>	Install a wire between the indicated terminals
Resistor	=>	Install a 1/4 w, 5% resistor in the position shown, except the 332 kΩ resistor used in SW13 will be the one removed from the amplifier.

Note that some terminals have multiple connections. The connections to banana plug terminals should be made temporary, because many have multiple wires to them.

c. Banana Plug Terminals

The connections for banana plug terminals are listed in Table 6. These connections are made using push-on connectors, which are crimped and soldered to the wires. When more than one

wire is routed to a terminal, crimp and solder all wires in the same push-on connector.

TABLE 6

BANANA PLUG TERMINAL WIRING

Terminal No.	Connections
T1	A-1
T2	A-2, T5
T3	P2-1
T4	B-13 at SW13
T5	T2, T6
T6	T5, T20
T7	SW12-1
T8	SW12-3, P3-1
T9	SW10-2
T10	T11
T11	T10, SW9-2
T12	SW8-2, P5-2
T13	T15, T20
T14	SW6-2, T23
T15	T13, T18
T16	SW7-2, A-13
T17	SW7-5, A-14
T18	T14, A-15
T19	P3-2, B-8
T20	T6, T13, resistor at P3-3
T22	SW7-3, SW7-4
T23	T14
T24	SW7-1, SW7-6
T31	A-9 and label MVO
T32	A-10 and label MCO
T33	A-12 and label SSO

Terminals T31, T32, and T33 are installed in the right side panel in the holes provided, see Figure B.7.

D. AMPLIFIER MODIFICATIONS AND WIRING

The LA-5600 amplifier requires modifications to enable interfacing to the control panel. The modifications include removal of components from the printed circuit board and removal of small sections of some conductor traces. The amplifier circuit board can be removed by unscrewing the large capacitors C26 and C27 and the corner standoffs. Disconnect connectors P1, P2, and P3 from the underside, to free the circuit board.

1. Component Removal

The removal of components should be done with a desoldering station tool. Remove the following components from the circuit board, for locations refer to the manufacturer's detailed drawings:

Jumper W1 or W2 whichever is installed
Potentiometers - R3, R55, R61, R36
Resistors - R5

The following modification steps refer to items by their orientation on the circuit board when viewing the board from above and the amplifier is positioned as is Figure 3.3 (i.e., fan on the left). Unsolder and remove just the top lead of resistor R11 from the board. Two conductor traces on the underside of the circuit board

must be cut (i.e., open circuited). The first trace runs from the top hole of jumper W1 to the top-center hole of R61. The second trace runs from the bottom hole of R3 to the top hole of R41. Remove a small section of conductor in these traces. The circuit board can now be remounted. Ensure proper polarity when reinstalling the large capacitors.

2. Amplifier Mounting and Cable B Installation

The amplifier can be mounted to the control panel by removing the two lower heatsink mounting screws, on the front heatsink (fan on the left), and bolting the control panel to the amplifier with round head bolts through the holes indicated in Figure B.10 of the back panel.

Cable B is a 20" length of multicolor ribbon cable with 15 conductors. It is positioned to run from the center of the circuit board, up and over the center of the top edge. With the cable in this position, wire no. 1 is on the left side (viewing amplifier with the fan on the left) of the cable. A 15 pin D-connector, female, is soldered onto one end of the cable in accordance with the D-connector wiring indicated in Table 7. The cable wires are then

soldered into the locations indicated in Table 8, referring to the manufacturer's detailed circuit diagrams if needed.

Once soldering is completed, shape the ribbon cable to conform the backside of the amplifier. This will require using a 90 degree turn fold on the ribbon cable. Mount the D-connector in a protective cover and to the connector in slot B of the back panel.

TABLE 7

D-CONNECTOR WIRING

	CABLE A			CABLE B	
Signal Name	Terminal on TB-1	Cable Wire no.	Connector A pin no.	Cable Wire no.	Connector B pin no.
VCS	1	1	1	1	1
COM	2	2	2	2	9
AUX	3	3	3	3	2
INH	4	4	4	4	10
MHC	5	5	5	5	3
COM	6	6	6	6	11
FAC	7	7	7	7	4
RAC	8	8	8	8	12
COM	9	9	6	9	5
MVO	10	10	9	10	13
MCO	11	11	10	11	11(NC)
COM	12	12	11	12	14
SSO	13	13	12	13	7
+15V	18	14	13	14	15
-15V	19	15	14	15	8
COM	20	16	15	-	-

3. Cable A Wiring

Cable A is a 22" length of 16 conductor ribbon cable. It should be routed from the left side of the amplifier, at TB-1, over the fan, across the front of the amplifier, and to D-connector A. The leftmost conductor is designated number 1. Install the cable wires at TB-1 in accordance with Table 7 using columns 1, 2, and 3. Prior to inserting the stripped ends of the wire in TB-1, twist and solder the multi-strand conductor. Reroute the fan leads over the top of Cable A, TB-1 pins 21 and 22. Solder a male D-connector on the other end of Cable A in accordance with columns 3 and 4 of Table 7, install a protective cover and connect to the connector in slot A of the back panel.

4. Motor Output Wiring

The wiring to MT+, MT- , and MT/SHLD is 18 AWG, cut lengths of 15 inches and inserted in a length of 1/4" PVC tubing. Insert three wires through Hole 3 of the back panel, see Figure B.10, and crimp and solder push-on connectors to the wires (control panel end). Connect these wires to MT+ (T30), MT- (T29), and MT/SHLD (T28). Route the wires across the front of the amplifier to TB-2,

and crimp and solder ring tongue connectors on the ends. When adding the connectors adjust the length of the wires to enable the following connections:

MT+ to terminal 8 of TB-2
MT- to terminal 7 of TB-2
MT SHLD to terminal 6 of TB-2

TABLE 8

CABLE B WIRING AT AMPLIFIER

Wire Number	Location
Wire 1	Top hole of W2 jumper position
Wire 2	At TpV_T
Wire 3	Top center hole of R61 position
Wire 4	Bottom hole of W1 jumper position
Wire 5	Solder to the top (removed) lead of R11
Wire 6	Top hole of R11 position, where lead was removed
Wire 7	Left hole of R61 position
Wire 8	Left hole of R55 position
Wire 9	Right hole of R55 position
Wire 10	Left hole of R5 position
Wire 11	Not used
Wire 12	Left hole of R36 position
Wire 13	Bottom hole of R3 position
Wire 14	Top hole of R3 position
Wire 15	At TpVo

5. Tachometer Output Wiring

The tachometer output wiring consists of one 18 AWG wire for the TG+ signal, and a shielded 18 AWG wire for TG-, with the shielding wire going to TG/SHLD. A 32" length of 18 AWG wire is inserted into a similar length of coaxial cable with the center conductor removed (refer to tachometer wiring for more detail). Route the shielded wire and another wire through Hole 4 of the back panel, crimp and solder push-on connectors to the shielded 18 AWG wire, the shielding wire, and the single wire ends. Connect the wires as indicated above. Route the wires around the back of the amplifier, inserting them in one of the slots of the heatsink assembly, and over the fan on the left side. Connect the TG+ wire to terminal 15, TG- wire to 16, and the shielding wire to 17.

6. AC Power to Amplifier

The AC power cord, installed in hole 2 of the back panel, is connected to the amplifier at TB-2. Install ring tongue connectors on the three conductors and connect the black wire (hot) to terminal 1 of TB-2, white (neutral) wire to terminal 5, and green (ground) to the amplifier chassis with the screw provided just below TB-2.

7. Amplifier Protective Cover

The amplifier cover, Figure B.11, is designed to prevent inadvertent shorting of the amplifier circuit board. It replaces the cover received with the amplifier. A balance control adjustment device is required in the amplifier cover to allow the student to adjust potentiometer R2. A remote adjustment device can be constructed from a suitable length of threaded rod, filed to fit into the potentiometer adjusting screw, bolted from above and below with nuts and washers, and an adjusting knob installed on top.

E. DC INPUT DEVICE

A need was found for a simple device which could be used to input a variable DC voltage for the velocity command signal. The availability of +15 and -15 volts at terminals T16 and T17 on the control panel could be used to deliver the variable DC input. Figure B.12 is a diagram of the device, which is installed in terminals T16, T17, and T18, and will output a variable DC voltage to its mounted banana plug terminal.

IV. SYSTEM TESTING

System testing was conducted to adjust current limiters in the amplifier, set tachometer scaling, and measure the characteristics of the filters which are incorporated in the amplifier. Prior to applying power to the system, one should review section 5.5 of the LA5600 Linear Amplifier Instruction Manual.

A. TACHOMETER OUTPUT SCALING

Scaling of the tachometer output determines the level of input command voltage required for a specific speed. The tachometer gain constant for the motor is 14.2 volts/krpm. A reasonable limit on input command signals is 10 volts and a maximum rpm of 5000 gives a desired tachometer scaling of 2 volts/krpm.

Potentiometer R53 on the amplifier circuit board is used to adjust the scaling of the tachometer output. To adjust the scaling, turn the system on and place it in a closed loop velocity feedback mode with high gain, and with the tachometer channel attenuation

set to zero, for help in setting this mode see Laboratory I in Appendix D. Apply a 2 volt command voltage and using a calibrated strobe adjust R53 until the motor speed comes to 1000 rpm.

B. CURRENT LIMIT SETTING

The LA5600 amplifier has two adjustable current limiting circuits. The current output of the motor is sensed by a resistor connected between the negative motor terminal and the amplifier power ground. The voltage drop across the resistor is amplified by a current sensing circuit. The output of this circuit used as an input to the current limiters and is available for use as the signal MVO.

The peak current limiter is adjusted to limit the peak output current of the output drivers. The setting of this limiter is accomplished with potentiometer R60. The RMS current limit circuit limits the length of time excessive current is applied to the motor. The time period is determined by the settings of potentiometer R60 for peak current and potentiometer R78 for RMS current. Increasing peak current and/or reducing the RMS current shortens the length of time excessive current is applied. When the set time has elapsed,

the RMS circuit activates the Amplifier Inhibit Clamp and lights the RMS current fault indicator LED. The amplifier is reset by toggling the Amplifier Inhibit Clamp OFF then ON. [Ref. 4:p. 3-2]

The setting of the current limiting potentiometers is performed as follows:

Rotate potentiometer R60 fully counterclockwise (CCW), this sets a 3.5 ampere peak current limit.
Rotate potentiometer R78 fully CCW then 1/2 turn CW.
Place the system in a closed loop position control mode with 50% velocity feedback damping and gain set to High/Min, (see Laboratory I for help in setting this mode).
Input a sinewave signal of 20 Hz and 1.0 volts peak to peak and observe the motor current at MVO on an oscilloscope.
Slowly increase the input signal frequency until the motor current trace shows a slight amount of jitter and reduce frequency to just below this point, approximately 600 Hz.
Slowly rotate R78 CCW until the RMS fault occurs. Then rotate CW slightly. (Final rotation from full CCW should be about 1/4 turn CW).
Reset the RMS fault, turn Amp Inhibit Clamp ON then OFF, and verify that the system does not fault at the last frequency setting. If a fault occurs, rotate R78 CW in small increments until a fault does not occur.

C. FILTER CHARACTERISTICS

The three installed filter networks can be characterized by their frequency response. Measurements of the lead filter and adjustable notch and lag filters at various settings were performed using a

HP3561A Dynamic Signal Analyzer and a dot matrix printer. The system was set up for the measurements with the motor/tach and position potentiometer leads disconnected from the system. The periodic noise source of the HP analyzer was used as the reference input signal to obtain the frequency response magnitude curves.

The response of these filters are useful to the more experienced student assigned to perform the advanced laboratory problems. The control panel is constructed to allow incorporation of user-built filter networks in place of, or in addition to, the installed filters.

1. Notch Filter

The response of the notch filter was measured with the noise source input to terminal T12, Velocity Feedback ON and output at terminal T11, refer to Figure B.6. This is an active filter so the system must be on to measure the response. Figures C.1, C.2, and C.3, Appendix C, show the response of the filter with both the adjusting potentiometers, P4 and P6, set at MIN, 1/2 MAX, and MAX respectively. With both potentiometers rotated to the same position, one obtains the narrowest stop band response. The notch frequency varies from 2012 Hz at MIN/MIN to 4162 Hz at MAX/MAX.

2. Lag Filter

The lag filter, an active filter, was measured with the noise input to VCS, and output at terminal T8. The effect of the Lag network response was compared to the response of the amplifier without the network. Figure C.4 shows the amplifier frequency response for a mid DC gain level. Figures C.5, C.6, and C.7 show the response for MIN, 1/2 MAX, and MAX settings of potentiometer P1. The effect of the potentiometer adjustment on the filter response is not proportional to it relative position. The response changes more rapidly with potentiometer settings near MAX.

3. Lead Filter

The lead filter response was determined with the system on, noise source input to terminal T10, and output at terminal T8. Figure C.8 shows the normal response of the amplifier at a frequency span of 2500 Hz, Figure C.9 shows the response with the lead filter. The user should note that the lead filter affects only the tachometer feedback channel and will have an influence on the system response when in a mode using closed loop velocity feedback.

V. LABORATORY EXPERIMENTS

The Basic Laboratory Series, enclosed in Appendix D, are experimental procedures, which explore the characteristics of the velocity and position control servo motor system. The procedures are designed to be an integral part of an undergraduate course in automatic control theory. A basic knowledge of linear systems (i.e., Laplace transforms and block diagrams), is recommended prior to commencing the laboratories. As the student proceeds through the series, knowledge is required in the use of Bode diagrams to depict open and closed loop response, Nichol's charts to determine open loop response from closed loop response data, and obtaining transfer functions from Bode diagrams using asymptote construction.

The first four laboratory procedures are written in a very explicit step by step fashion in order to familiarize the student with the operation of the test equipment and output signal locations. The remaining laboratories in the series rely on the student's accumulated experience to set up the test equipment and obtain the

desired experimental results. The laboratory procedures are designed to be performed in two hours. Some of the lengthy topics are broken down into separate procedures. The following sections are a general description of the laboratory procedures, required test equipment, and knowledge skills required to complete the labs. A complete set of typical laboratory write-ups with results for each lab in the series are enclosed in Appendix E for use by the instructor.

A. GENERAL DESCRIPTION

1. Laboratory I - System Familiarization

Lab I provides the student with the basic knowledge required for system start-up and balancing. The discussion section describes the use of all switches, terminals, and potentiometers. The student aligns the system in closed loop velocity and position control configurations and performs a few basic tests of the system controls.

2. Laboratory II - Open Loop Velocity and Position Control

Lab II demonstrates the limitations of operating a motor in an open loop velocity and position control mode. The student measures the time response of the system to a step input.

3. Laboratory III - Closed Loop Velocity Control

This lab is broken down into two procedures to meet the two hour time criteria.

a. Laboratory III A - Basics

Measurements are taken of the closed loop time constant and settling time for several forward gain settings to determine its effect on the system.

b. Laboratory III B - Open and Closed Loop Transfer Functions

A spectrum analyzer is used to generate open and closed loop frequency response curves. Data from the curves is tabulated and plotted in Bode form. Transfer functions are written for the open loop response from the closed loop data (through a Nichol's chart) and from the measured open loop response, then compared.

4. Laboratory IV - Closed Loop Position Control

Lab IV is broken down into two separate procedures. As stated previously, these laboratories are written with general procedural steps and rely on the student's experience to set up the test equipment and obtain the desired results.

a. Laboratory IV A - Basics and Transfer Functions

Lab IV A covers the same material as Lab III A and III B using a position control mode.

b. Laboratory IV B - Velocity Damping

This lab demonstrates the concept of using a velocity signal to damp a system with oscillatory behavior.

B. LABORATORY TEST EQUIPMENT

The test equipment required to adequately perform the laboratory procedures and specific equipment used to complete the example laboratory write-ups are listed in Table 9. Suitable equipment may be substituted for those indicated, ensuring the lab procedures are modified accordingly.

TABLE 9

REQUIRED TEST EQUIPMENT

Name/Function	Model Used
D.C. Voltmeters	Hewlett Packard HP 427A
Pulse/Function Generator	Wavetek Model 145
Two Channel Chart Recorder with linear speed to 125 mm/sec	Gould 220
Spectrum Analyzer, transfer function capability	Hewlett Packard HP 3582A
Plotting interface to spectrum analyzer	Hewlett Packard HP 85 Microcomputer

C. SKILLS/KNOWLEDGE REQUIREMENTS

The minimum basic skills necessary for the student to perform the laboratories are listed in Table 10. Each lab builds upon the knowledge gained in the previous one and complete instruction in the basic system capabilities and applicable control theory is covered.

TABLE 10

STUDENT SKILLS REQUIREMENTS

Laboratory No.	Skills/Knowledge Required
I	Basic servo motor block diagram, meaning of terms; velocity feedback, position feedback, command signal
II	System type numbers, terms; open loop system, system gain, time constant, settling or transient time
III	Construction of Bode diagrams from closed loop response data, use of a Nichol's chart to obtain open loop response from closed loop data, determination of a transfer function from an open loop Bode diagrams using asymptote construction Terms; closed loop system, forward gain, error signal, summing junction, unity feedback, stability
IV	Terms; closed loop position control, instability, second order system, damping ratio ξ, velocity feedback damping, characteristic equation

VI. ADVANCED TOPICS

The advanced topics are divided into two sections, linear control including nonlinear aspects and digital control. The problems in these sections deal with alternate methods of controlling a servo system, studying second order effects such as mechanical resonances, and converting an analog controlled system to digital control. The digital control problems range from simple samplers to complete microprocessor base compensators. Rather than creating laboratory procedures, the topics are written as projects and are enclosed in Appendix F. The scope of the project is left to the instructor and the experimental steps are left to the student.

It is strongly recommended that a complete simulation study, of the proposed solution for the project, is conducted prior to building any hardware. Specific values of circuit components in the amplifier hardware are available in the detailed circuit diagrams. All designs should be connected to the system through the control panel, modifying the existing wiring is not recommended.

VII. CONCLUSION

The requirement to design this laboratory servo system arose from the need to replace an aged system presently used in an automatic control theory course at the Naval Postgraduate School. The primary factors driving construction of the new system were high bandwidth to allow use of a spectrum analyzer to obtain an accurate frequency response measurement and simplicity of operation. The results, included in the example laboratory reports, demonstrate the ability to accurately measure the system response with the spectrum analyzer. During the writing of this thesis, students in a control theory course performed the laboratory experiments on the new system. Student comments indicated that the system was easy to operate and an enjoyable learning experience. The instructor was very satisfied with the operation and response of the system.

The construction and integration steps presented, were written to provide sufficient information for building additional units. It is

recommended that the control panel construction be performed by a qualified machinist.

Comparisons were performed between the designed system and the MCSL Motomatic Control System described earlier. The results showed that both systems have comparable bandwidths and safety features. Operation of the MCSL system is straightforward and produces satisfactory experimental results. The designed system does have some advantages over the MCSL system. These include the ability to modify system design if desired using the available detailed circuit diagrams, adjustable compensation filters installed in the hardware, control panel operation performed with switches vice wiring, and the detailed construction information in this thesis to aid in maintaining the system. The MCSL system's primary advantage is that only the construction of filters and gain adjustment devices is required to place the system in operation.

In summary, the designed system has met all the requirements set forth in the goals of the thesis and has proven to be easy to operate, to produce desirable and accurate results and to be a viable instructional tool.

APPENDIX A

FREQUENCY RESPONSE SIMULATION PROGRAMS

DSL programs used to determine the closed loop frequency response for justification of the proposed servo system components.

```
TITLE SERVO MOTOR FREQUENCY RESPONSE
*      CLOSED LOOP VELOCITY CONTROL
COMPLEX S,GA,GM,GEQ,GCL
*      MOTOR AND AMPLIFIER CONSTANTS
CONST KE = 8.308E-2, KG = 0.1356, TAUE = 2.3E-3, TAUM = 11.3E-3
CONST A =20, K = .141,DB3 = -4.7077
*      K = .141 GIVE 1.0 VOLTS/500 RPM SCALING TO THE TACHOMETER
DYNAMIC
*      THE AMPLIFIER HAS A GAIN BANDWIDTH PRODUCT OF 1200 * 2000 HZ
*      FOR GAIN LESS THAN 1200 THE BANDWIDTH IS LARGER
       F = 1200.*2000./A
       TAUA = 1./(2.*PI*F)
*      EQUATIONS TO GENERATE FREQUENCY SWEEP OF FOUR DECADES
       LOGW = TIME
       W = 10.**LOGW
       S = CMPLX(0.,W)
*      TRANSFER FUNCTIONS
       GA = A/(S*TAUA + 1.)
       GM = (1./KE)/((S*TAUE+1.)*(S*TAUM + 1.))
       GEQ = GA*GM*K*KG
       GCL = GEQ/(GEQ+1.)
*      MAGNITUDE AND PHASE CALCULATIONS
       MAG = 20.*GAIN(GCL)
       DEG = RADEG*PHASE(0.,GCL)
*      CONTROL AND GRAPH STATEMENTS
CONTRL FINTIM = 4,DELT = .005
SAVE .005,MAG,DEG,W,DB3
GRAPH (G1,DE=TEK618,PO=0,1) W(AX=LOG,LO=1,NI=4,LE=6,UN='RAD/SEC'),...
       MAG(LE=7,UN='GAIN(DB)',SC=20,LO=-40,NI=8),...
       DEG(LE=7,UN=DEGREES,SC=30,LO=-240,NI=8,PO=-1.),...
       DB3(AX=OMIT,LE=7,SC=20,LO=-40,NI=8)
LABEL (G1) SERVO SYSTEM FREQUENCY RESPONSE SIMULATION
LABEL (G1) VELOCITY CONTROL-CLOSED LOOP
END
STOP
```

Figure A.1 DSL Frequency Response Program for Velocity Control

```
TITLE SERVO MOTOR FREQUENCY RESPONSE
*      CLOSED LOOP POSITION CONTROL
COMPLEX S,GA,GM,GEQ,GCL
*      MOTOR AND AMPLIFIER CONSTANTS
CONST KE = 8.308E-2, TAUE = 2.3E-3, TAUM = 11.3E-3
CONST A =5., DB3 = -3.
DYNAMIC
*      THE AMPLIFIER HAS A GAIN BANDWIDTH PRODUCT OF 1200 * 2000 HZ
*      FOR GAIN LESS THAN 1200 THE BANDWIDTH IS LARGER
       F = 1200.*2000./A
       TAUA = 1./(2.*PI*F)
*      EQUATIONS TO GENERATE FREQUENCY SWEEP OF FOUR DECADES
       LOGW = TIME
       W = 10.**LOGW
       S = CMPLX(0.,W)
*      TRANSFER FUNCTIONS
       GA = A/(S*TAUA + 1.)
       GM = (1./KE)/((S*TAUE+1.)*(S*TAUM + 1.))
       GEQ = GA*GM/S
       GCL = GEQ/(GEQ+1.)
*      MAGNITUDE AND PHASE CALCULATIONS
       MAG = 20.*GAIN(GCL)
       DEG = RADEG*PHASE(0.,GCL)
*      CONTROL AND GRAPH STATEMENTS
CONTRL FINTIM = 4,DELT = .005
SAVE .005,MAG,DEG,W,DB3
GRAPH (G1,DE=TEK618,PO=0,1) W(AX=LOG,LO=1,NI=4,LE=6,UN='RAD/SEC'),...
       MAG(LE=7,UN='GAIN(DB)',SC=20,LO=-40,NI=8),...
       DEG(LE=7,UN=DEGREES,SC=30,LO=-240,NI=8,PO=-1.),...
       DB3(AX=OMIT,LE=7,SC=20,LO=-40,NI=8)
LABEL (G1) SERVO SYSTEM FREQUENCY RESPONSE SIMULATION
LABEL (G1) POSITION CONTROL-CLOSED LOOP
END
STOP
```

Figure A.2 DSL Frequency Response Program for Position Control

APPENDIX B

SCALE DRAWINGS FOR CONTROL SYSTEM CONSTRUCTION

This appendix contains the scale drawings of parts required for construction of the system control panel, equipment track, amplifier cover, and D.C. input attachment. All drawings are shown at full scale unless otherwise noted. All dimensions are in decimal or fractional inches. Cutout or drilled sections hidden from view are indicated by a broken line.

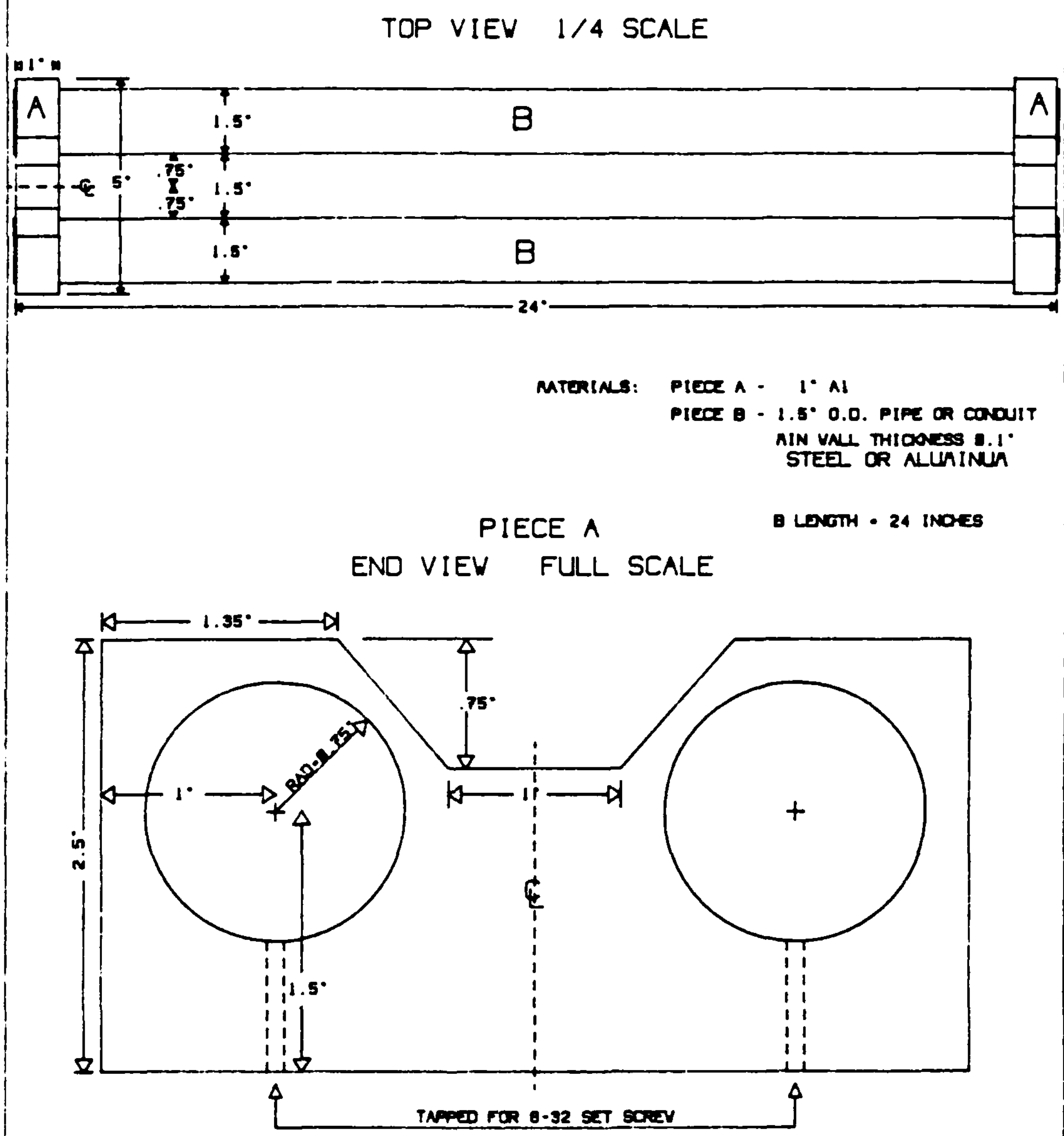


Figure B.1 Track Base

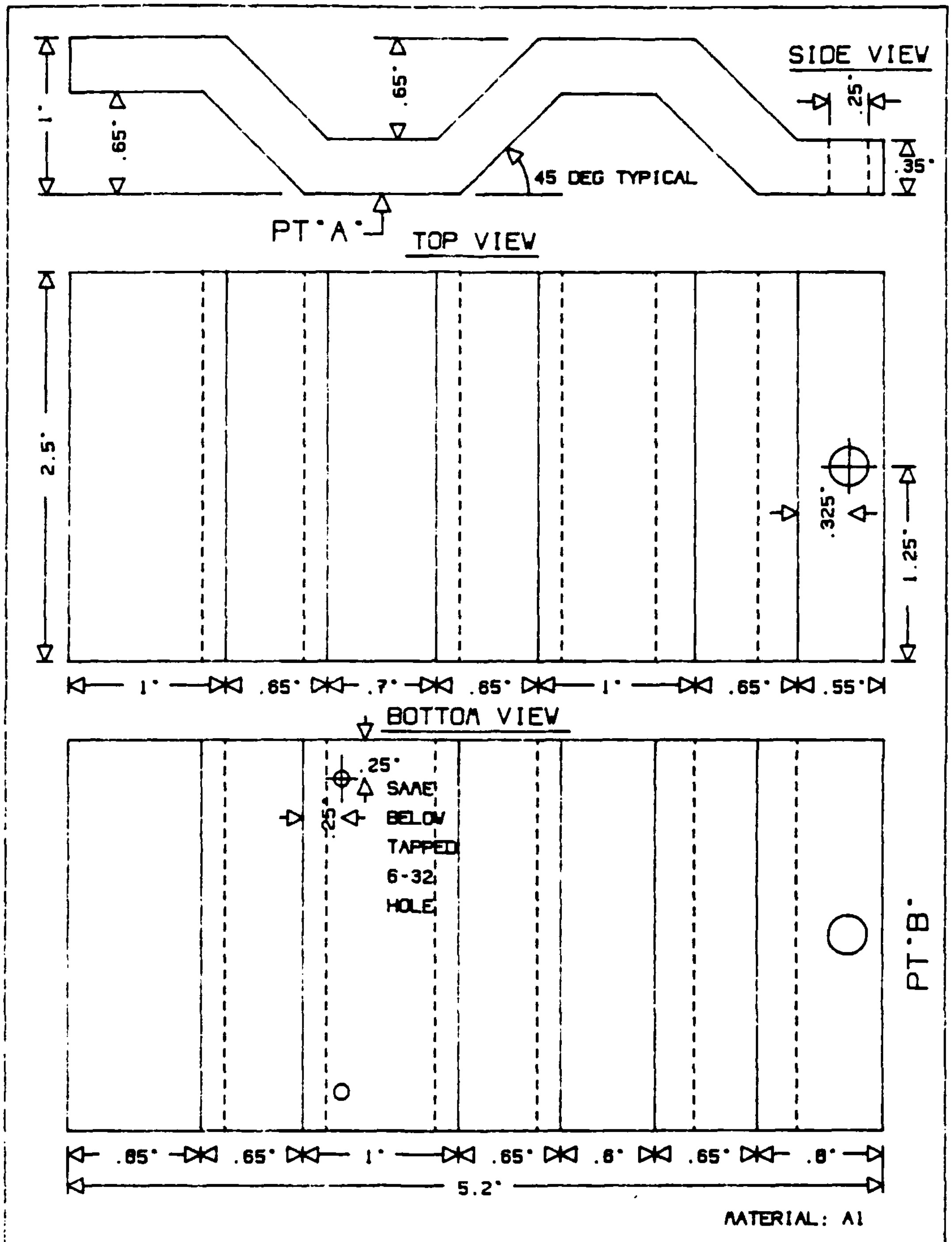


Figure B.2 Equipment Sled

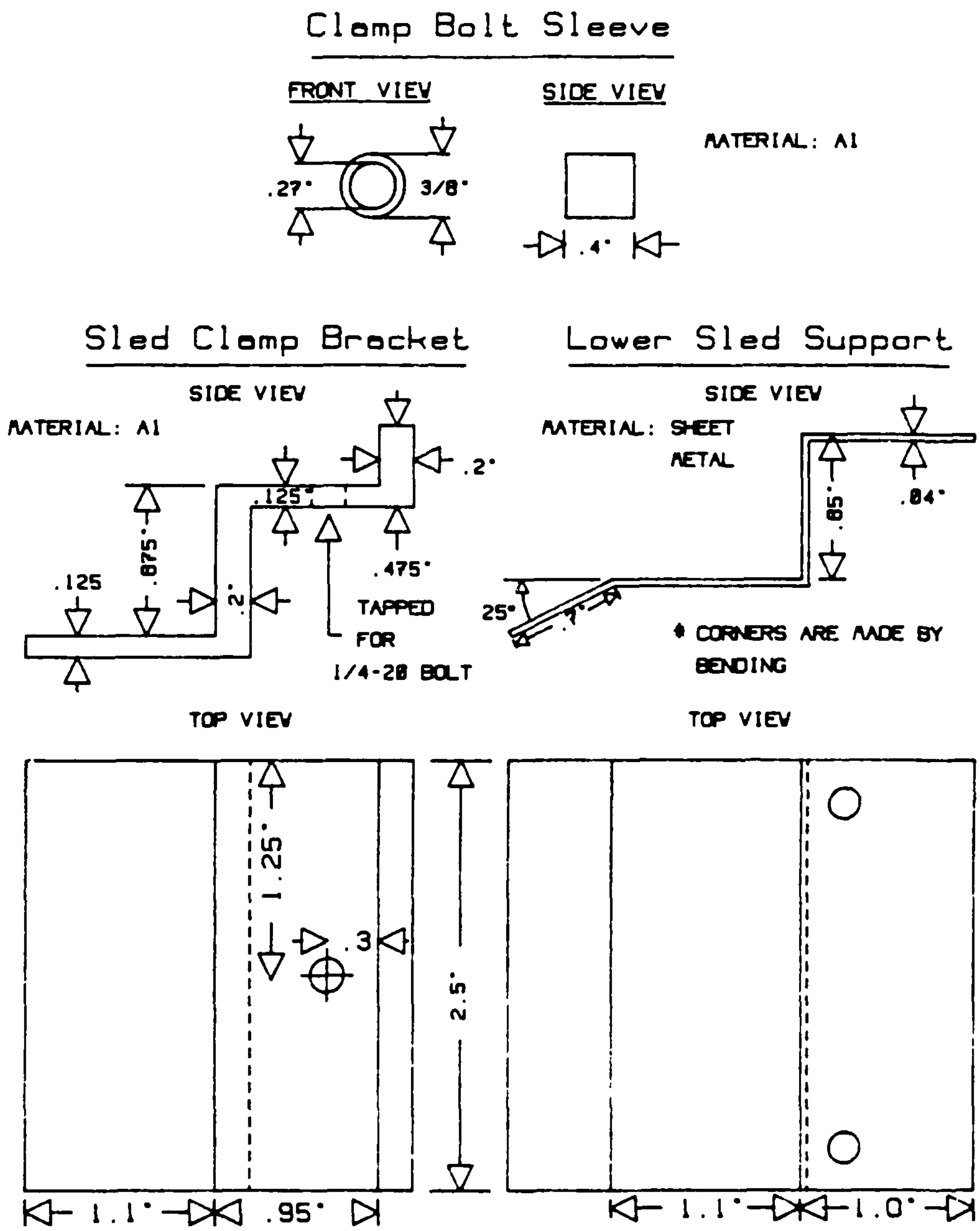


Figure B.3 Equipment Track Parts

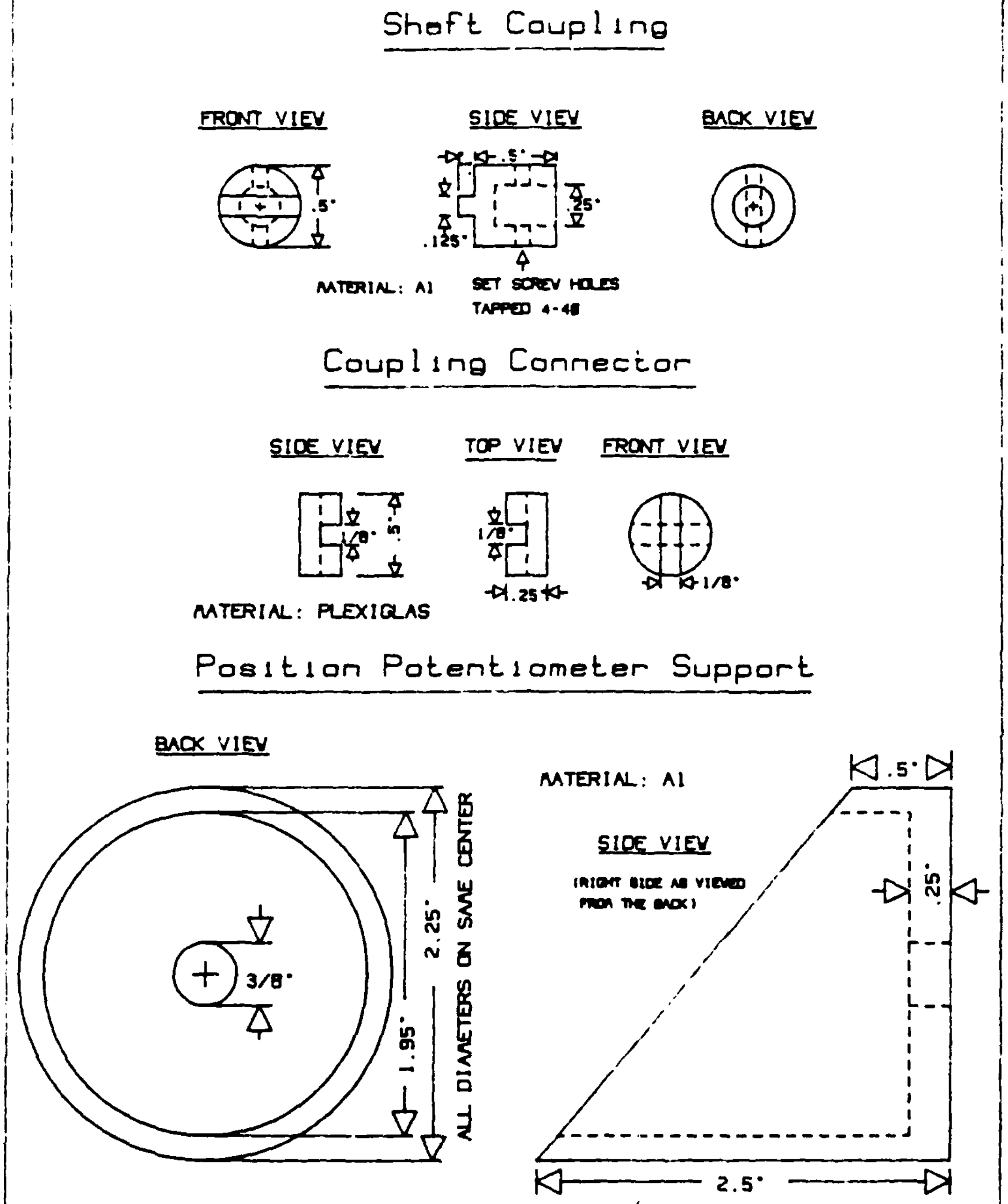


Figure B.4 Coupling and Potentiometer Support

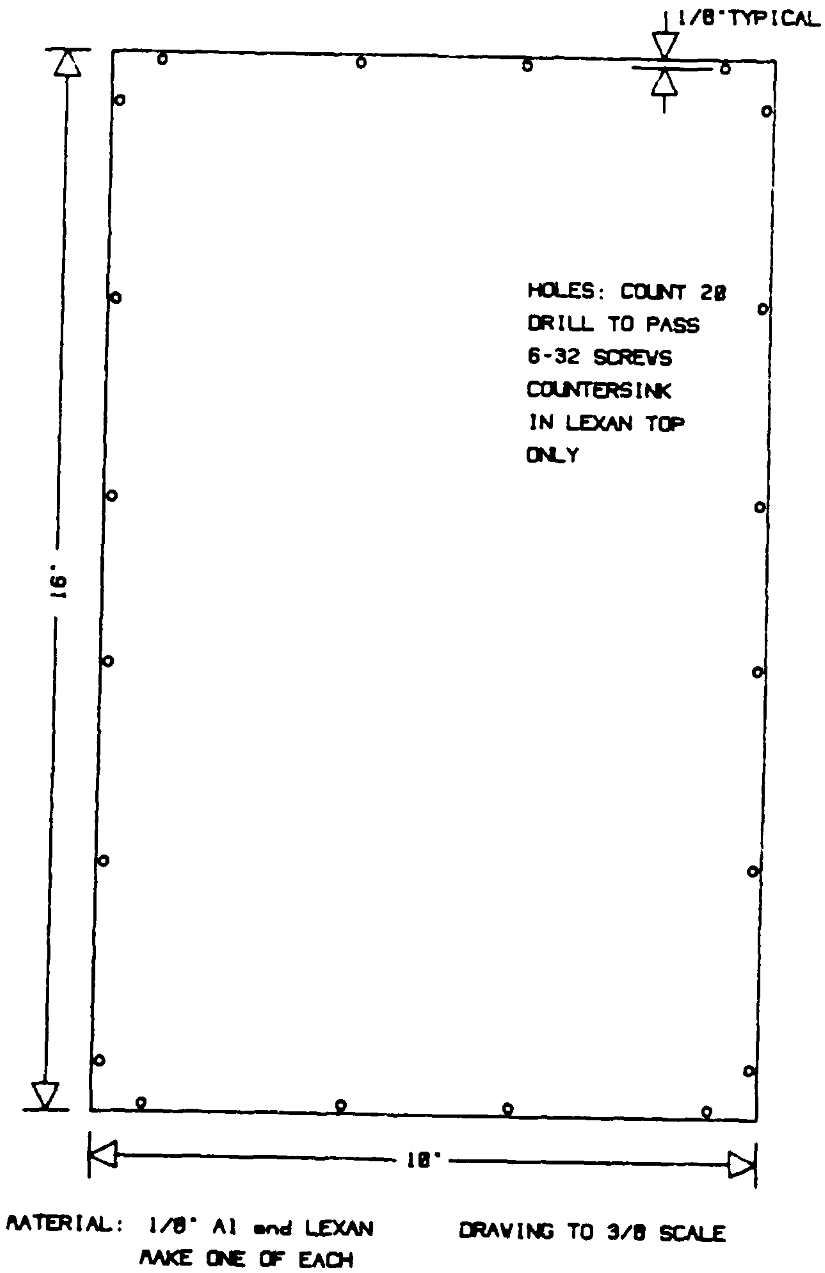
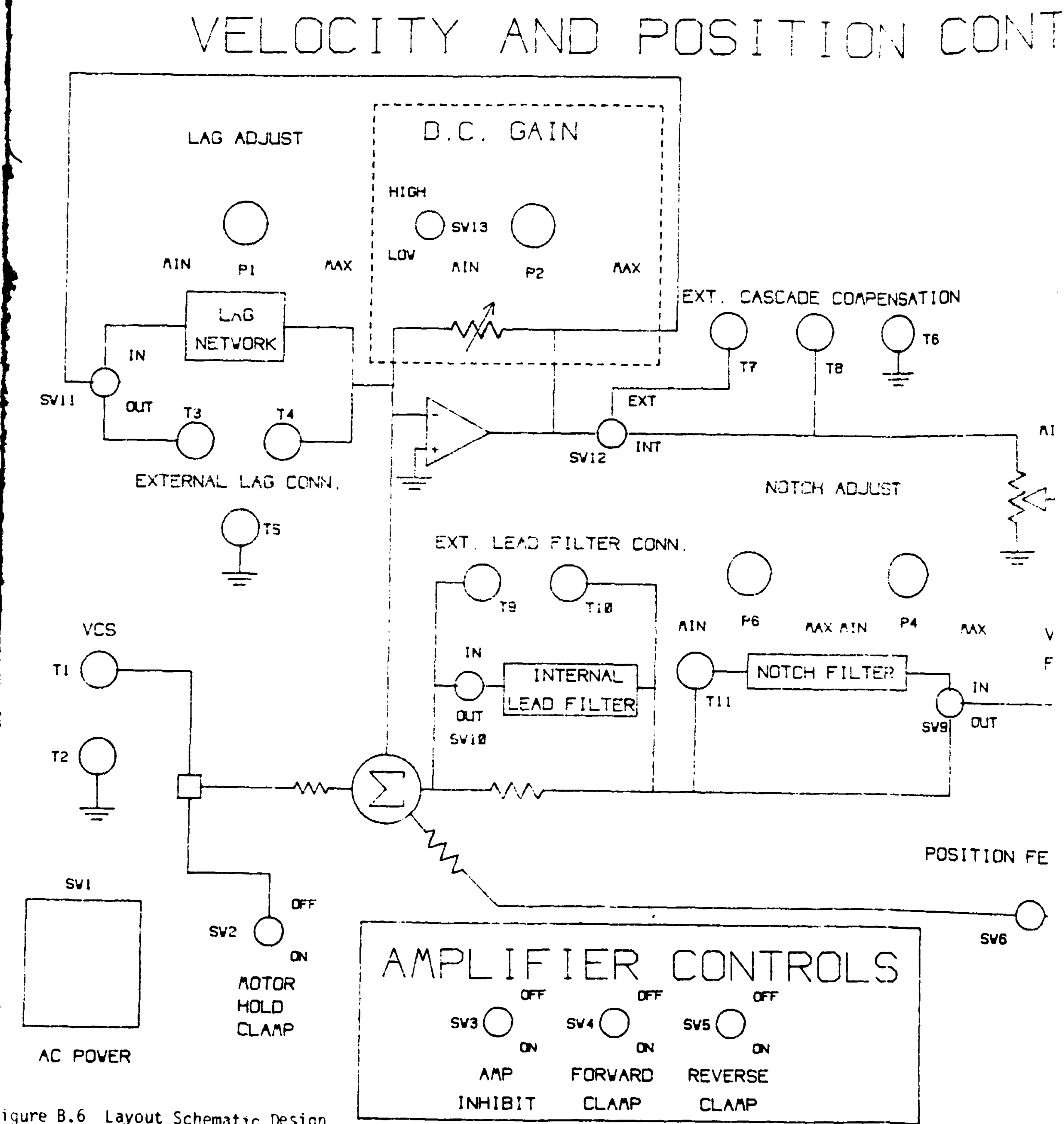
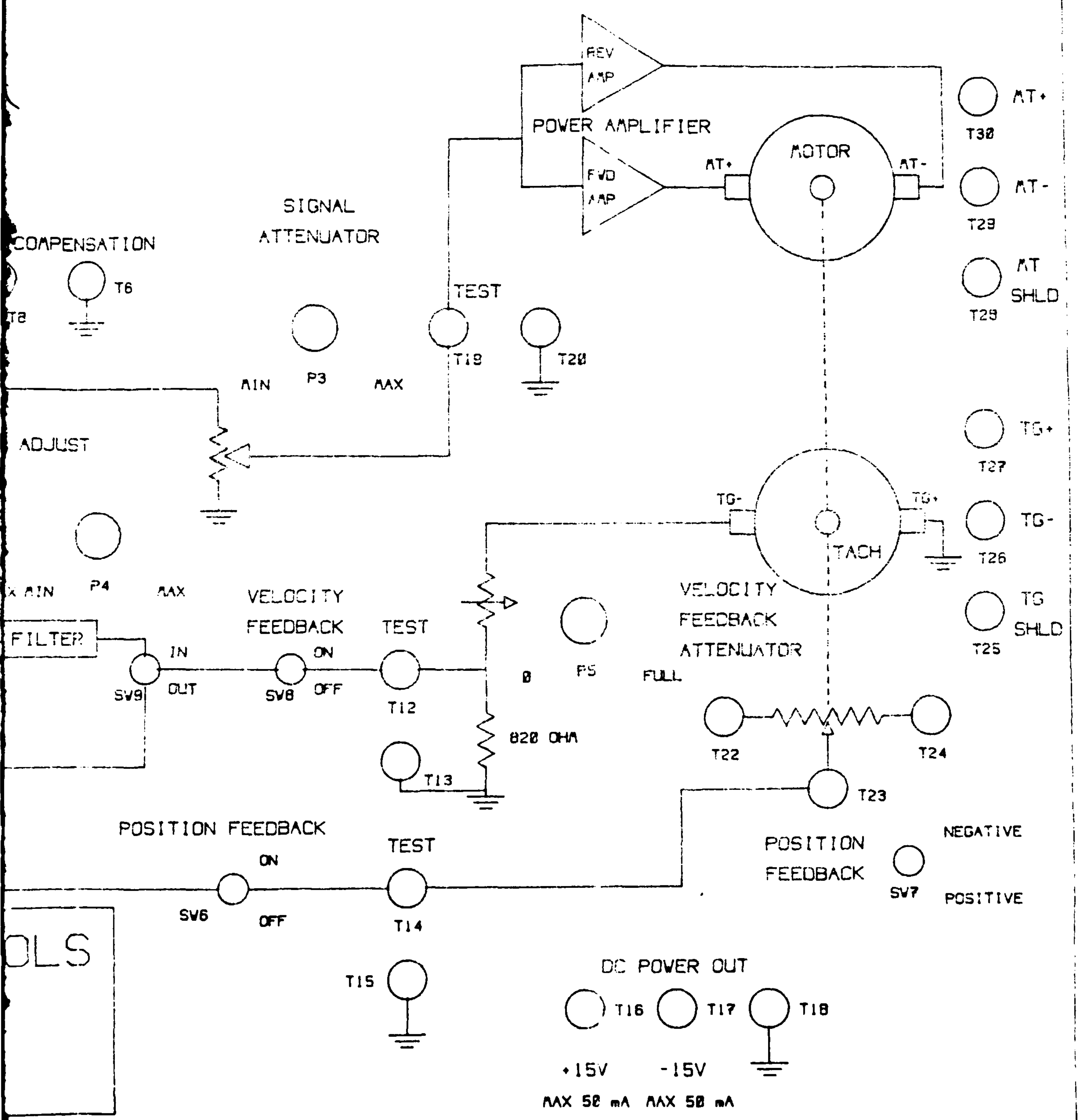


Figure B.5 Top Panels



igure B.6 Layout Schematic Design

ON CONTROL SERVO SYSTEM



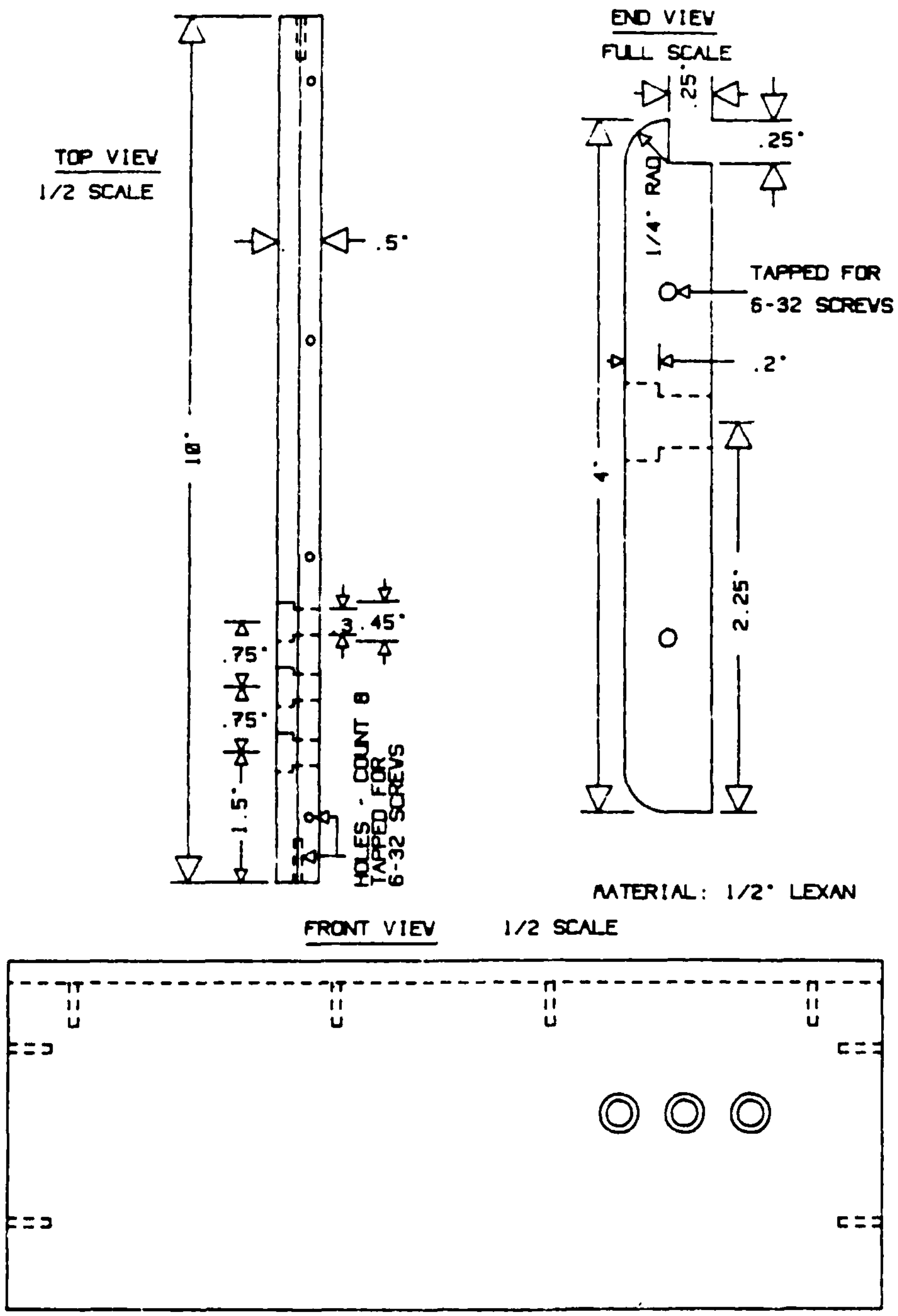


Figure B.7 Right Side Panel

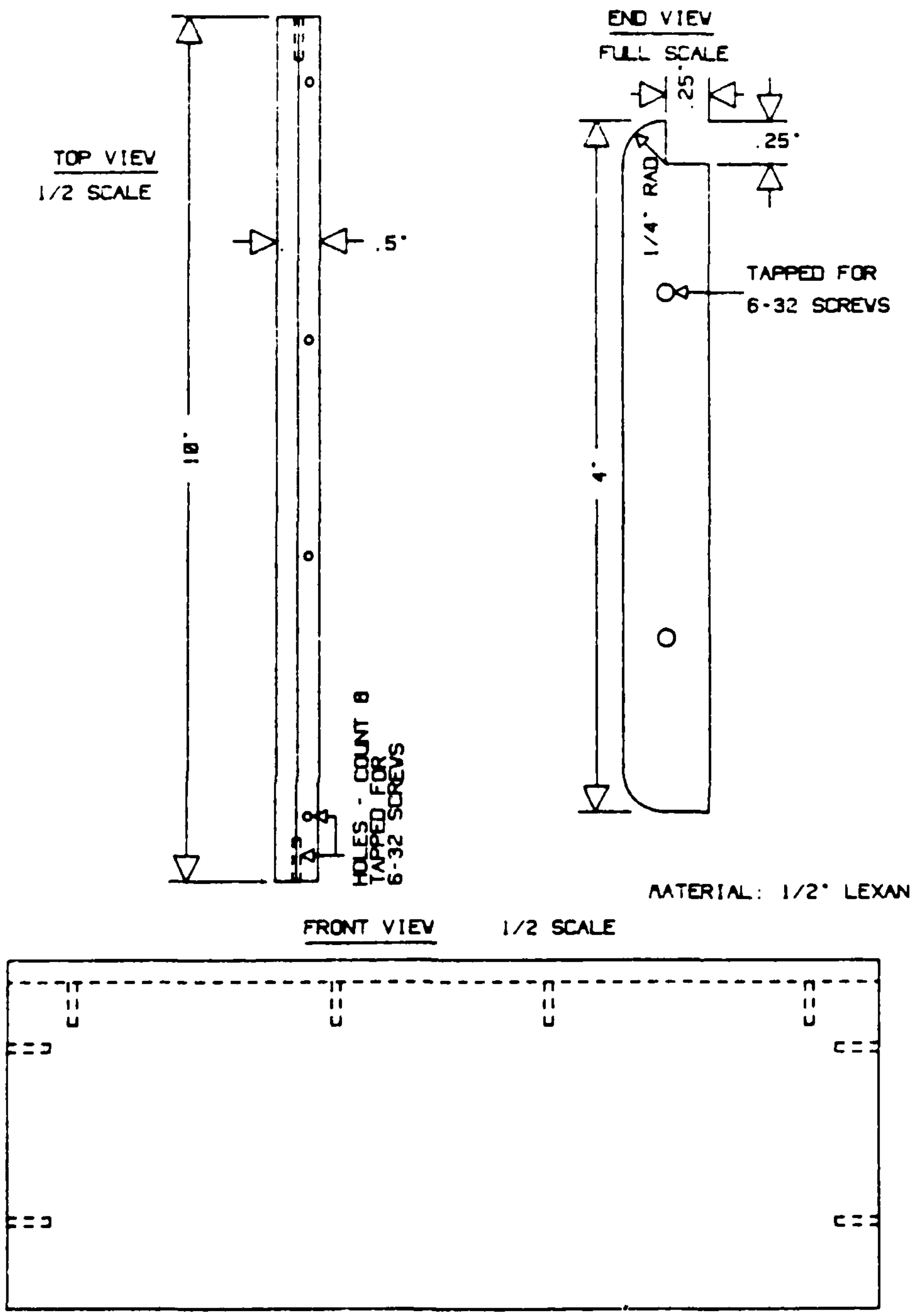


Figure B.8 Left Side Panel

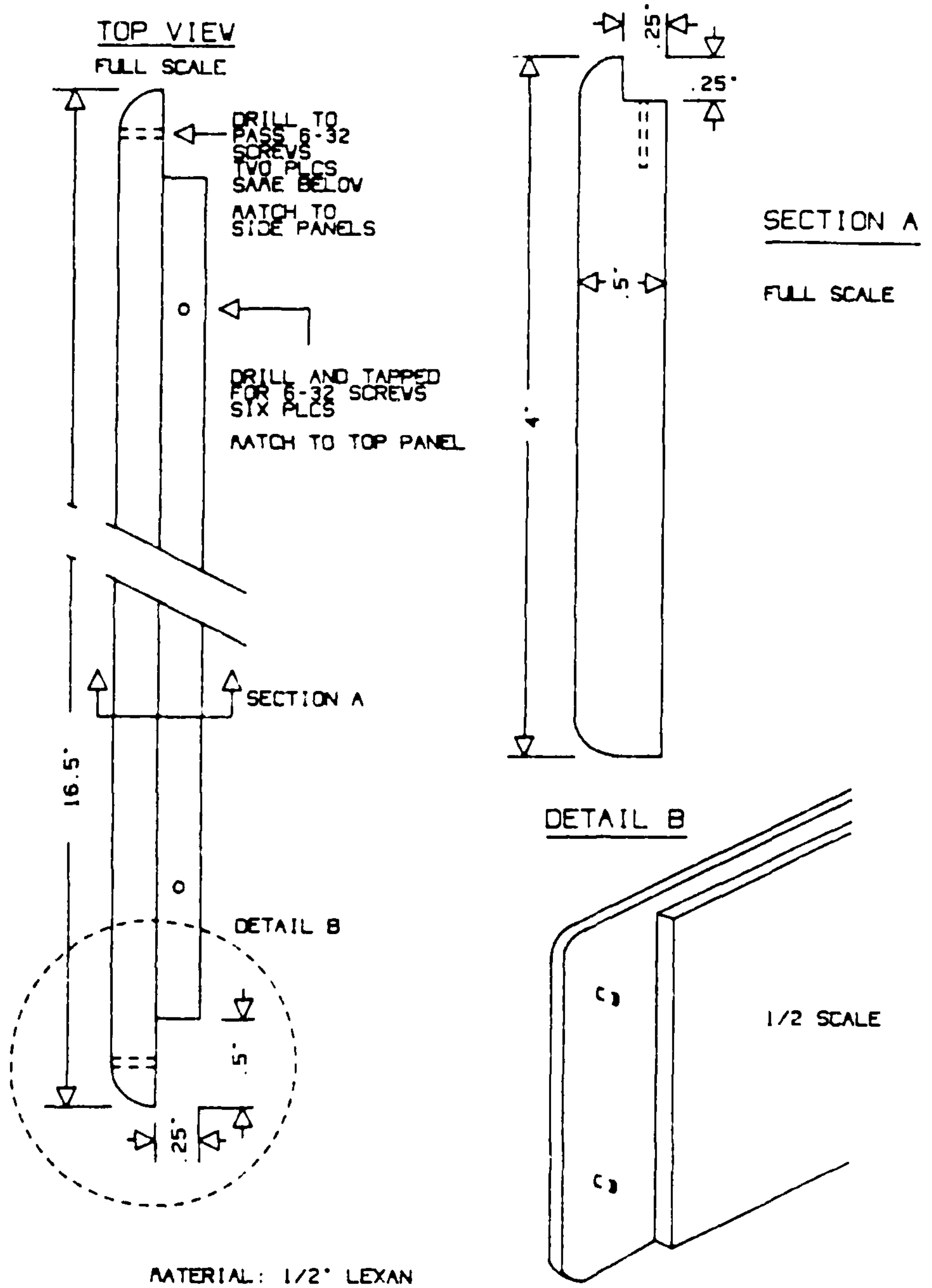


Figure B.9 Front and Back Panels
(Back Panel has additional cutouts, see Figure B.10)

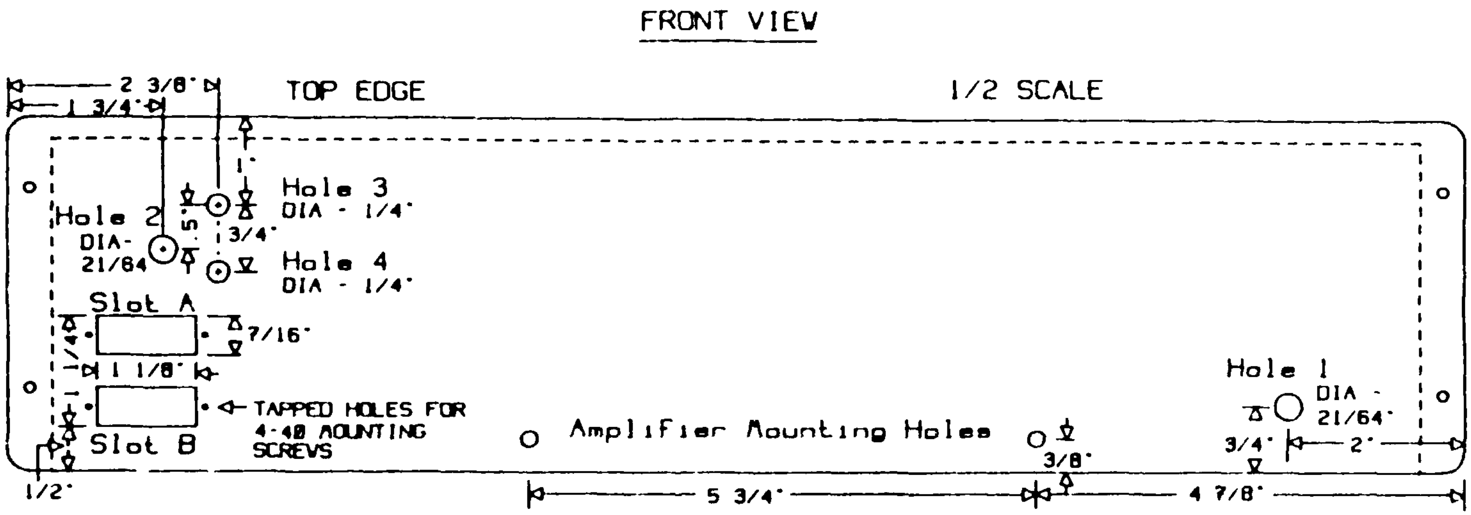


Figure B.10 Additional Modifications to Back Panel

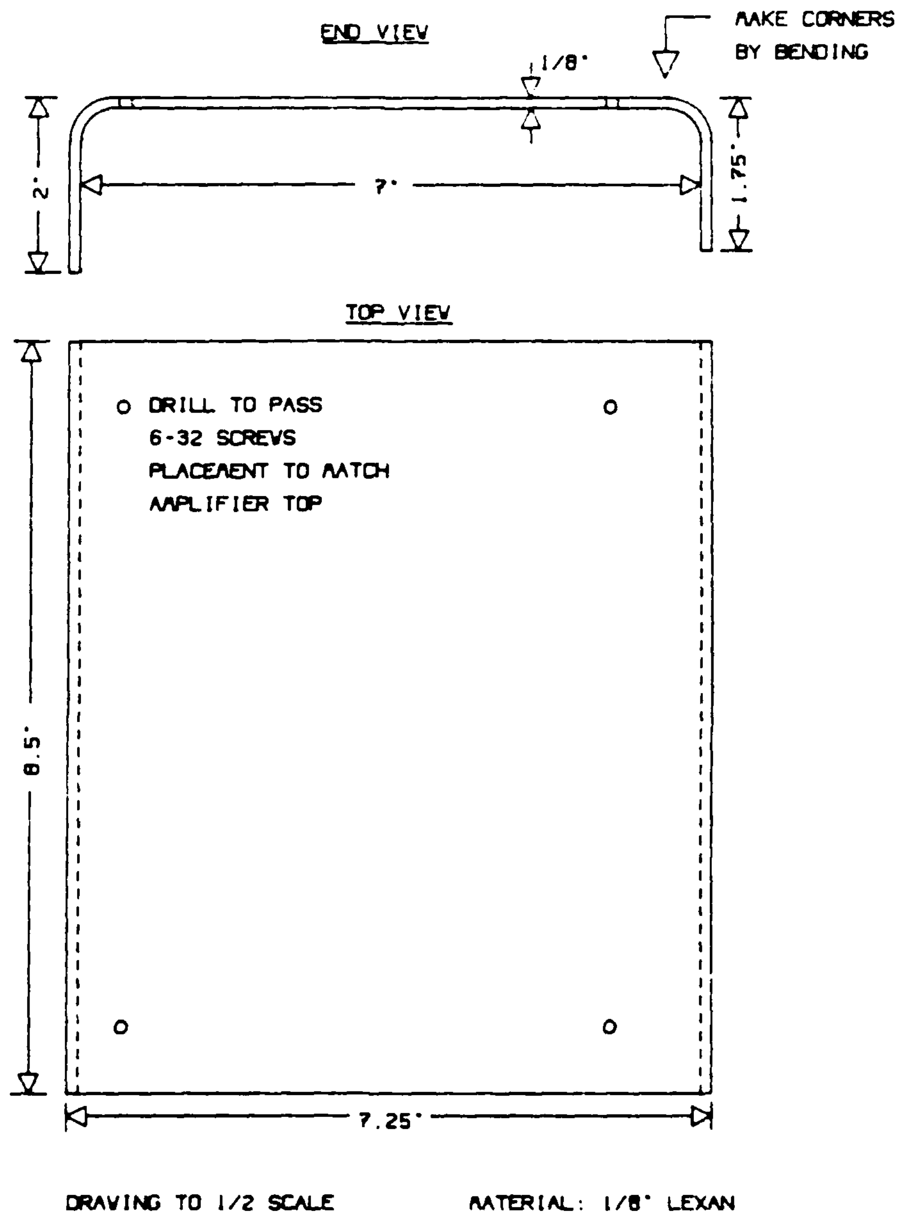


Figure B.11 Amplifier Protective Cover

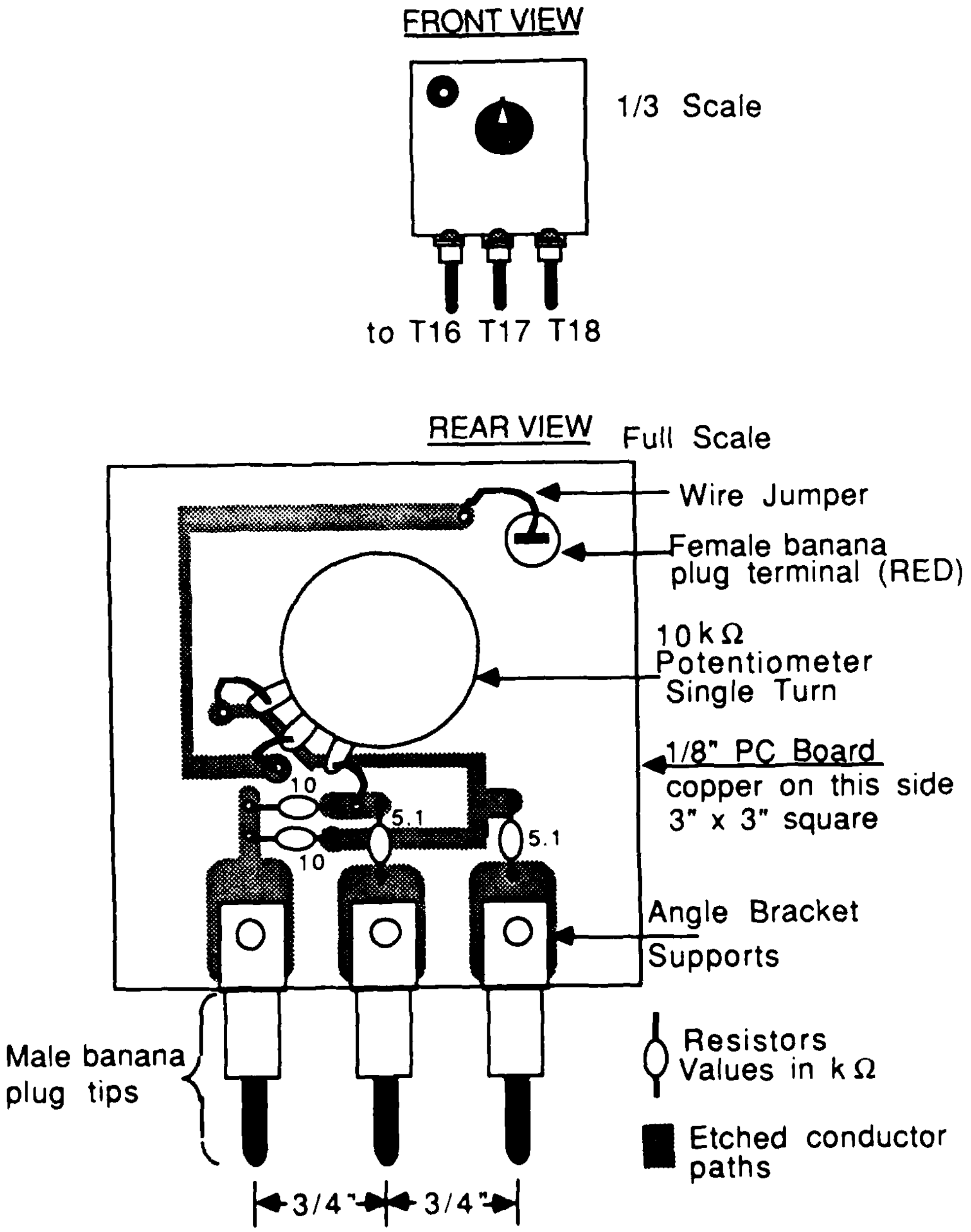


Figure B.12 D.C. Input Attachment Layout

APPENDIX C

FILTER FREQUENCY RESPONSE PLOTS

The notch, lag, and lead filters are characterized by their frequency response, obtained with a spectrum analyzer, for several potentiometer settings.

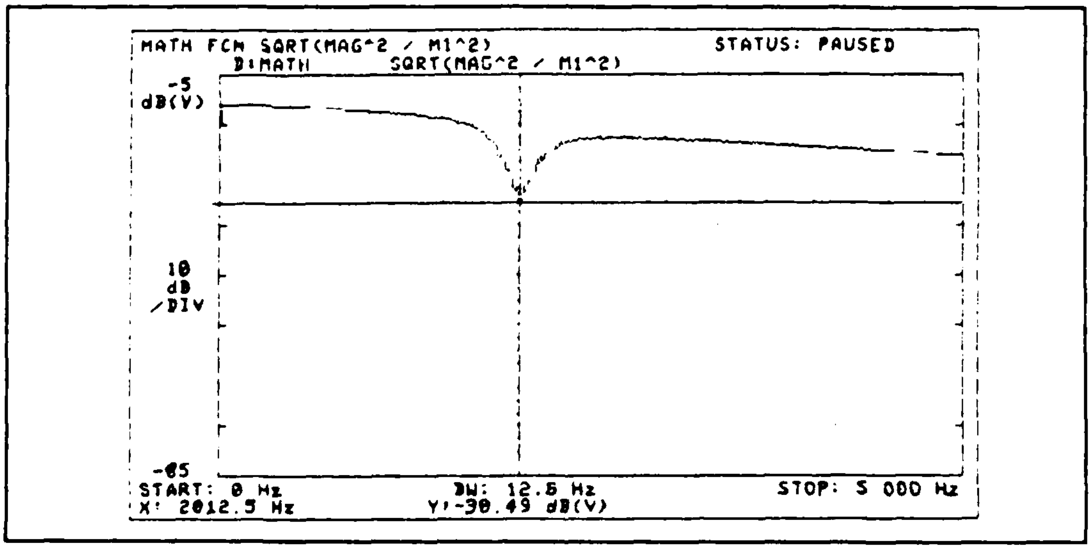


Figure C.1 Notch Filter Response - Setting MIN

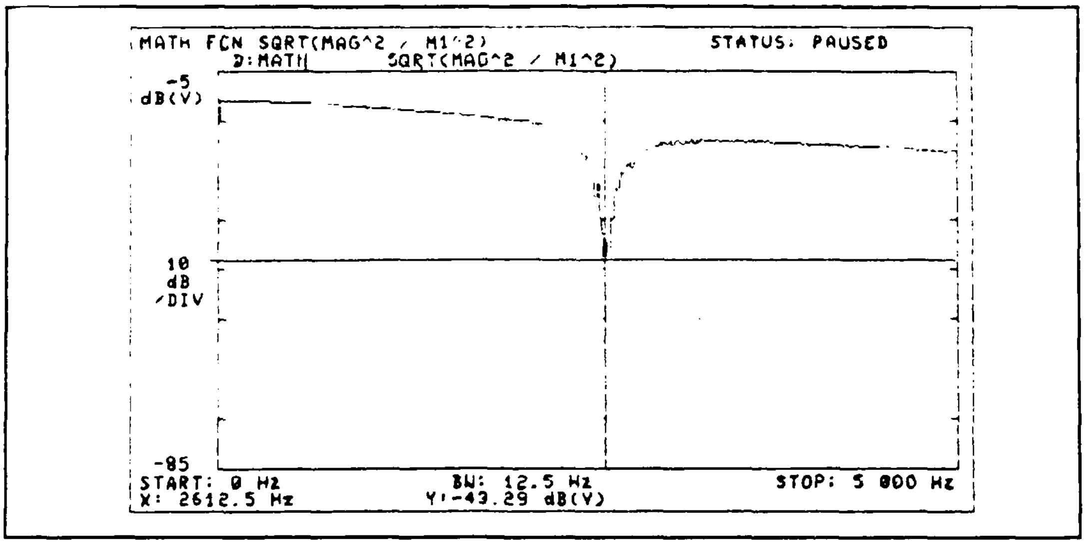


Figure C.2 Notch Filter Response - Setting 1/2MAX

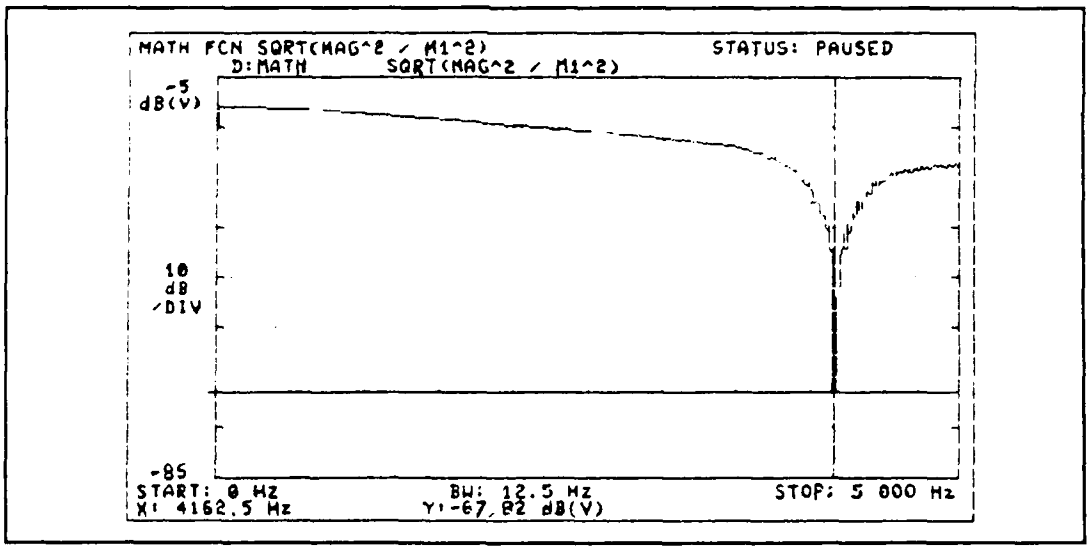


Figure C.3 Notch Filter Response - Setting MAX

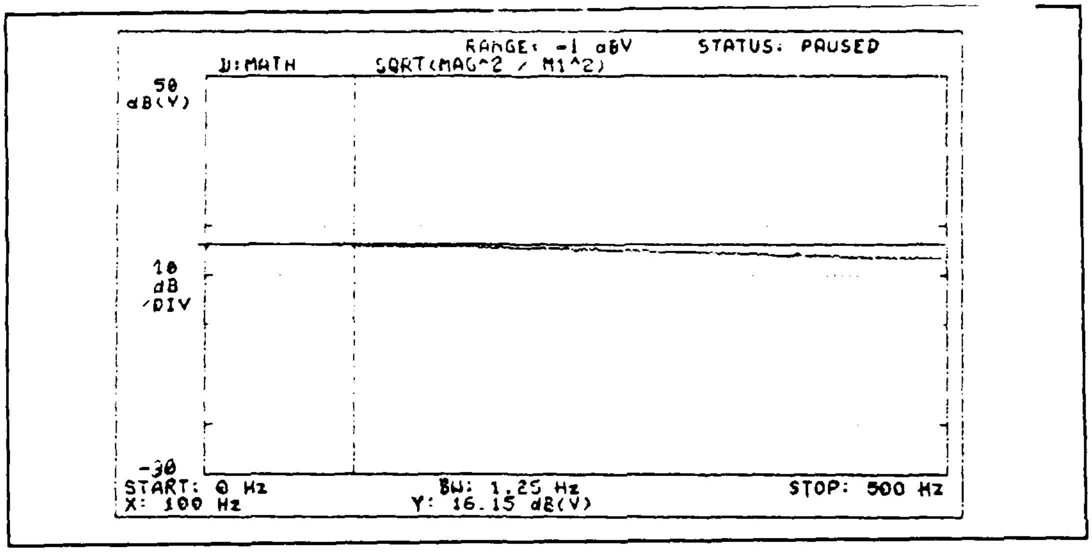


Figure C.4 Normal Amplifier Response - Gain 1/2MAX/LOW

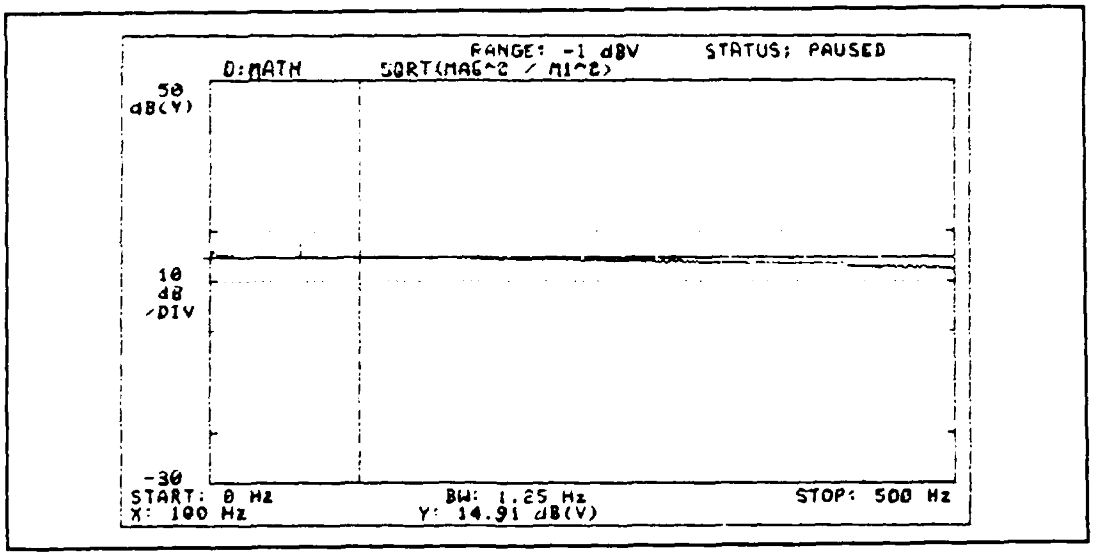


Figure C.5 Lag Filter Response - Setting MIN

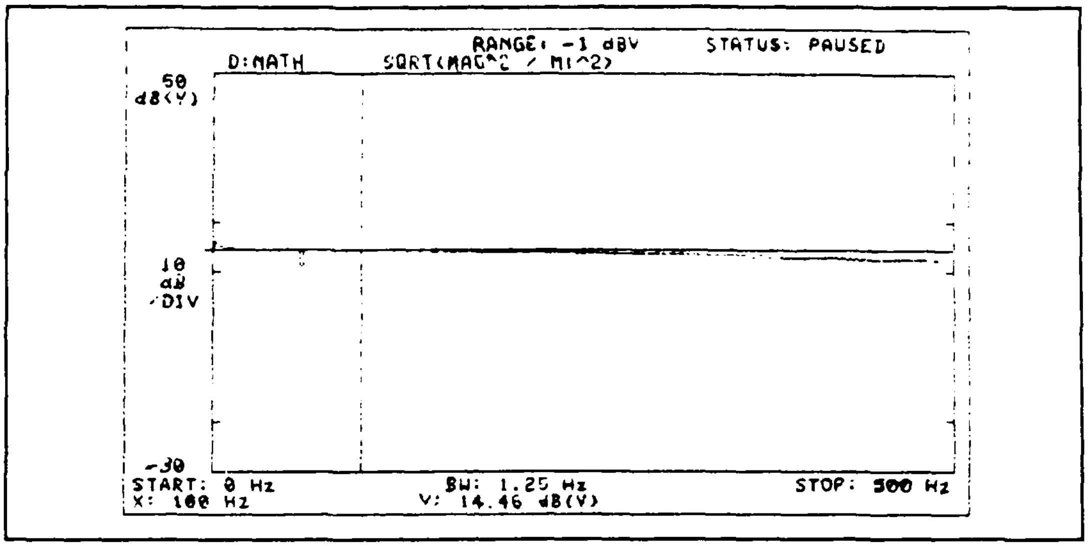


Figure C.6 Lag Filter Response - Setting 1/2MAX

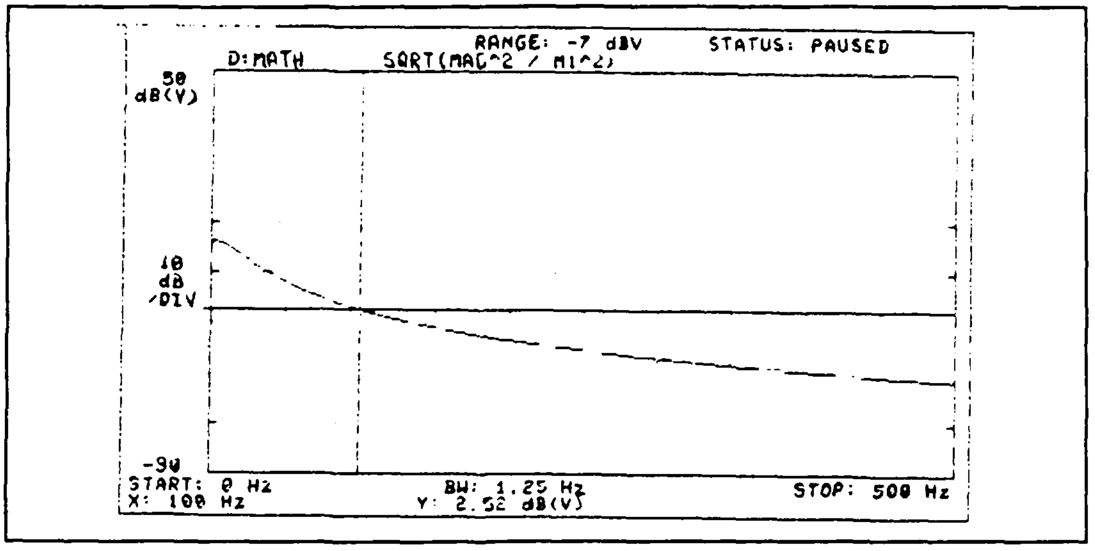


Figure C.7 Lag Filter Response - Setting MAX

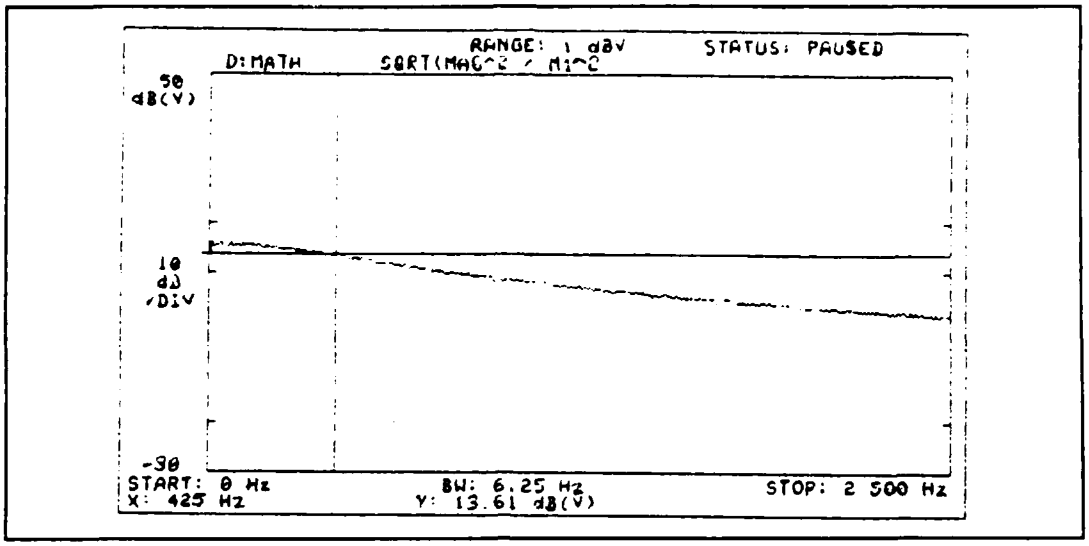


Figure C.8 Normal Amplifier Response

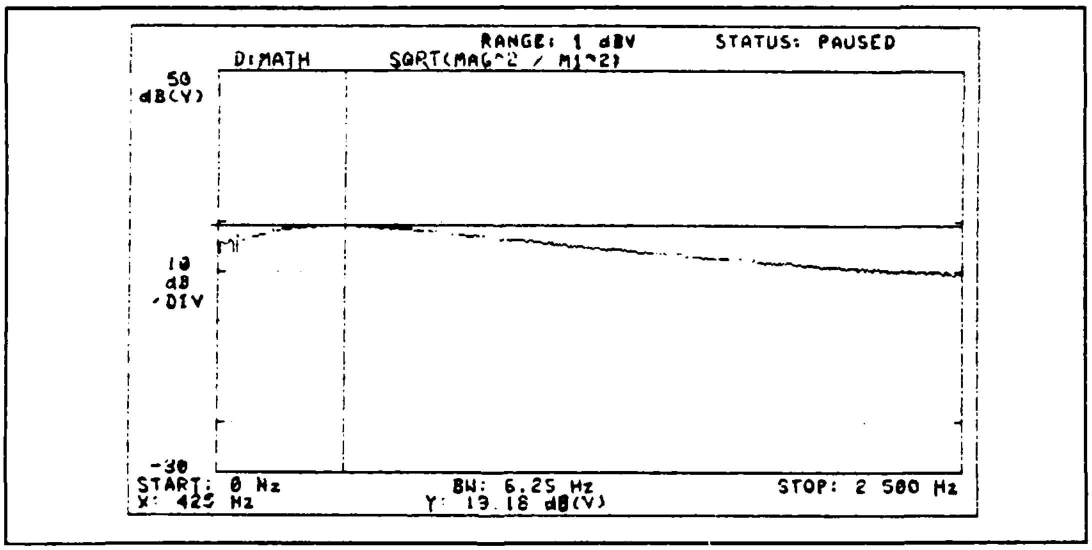


Figure C.9 Lead Filter Response

APPENDIX D

PREFACE TO THE BASIC LABORATORY SERIES

The Laboratory Experiments in this series are designed to be completed in a two hour time period. The first laboratory familiarizes the student with the operation and control of the Velocity and Position Control System. Laboratories II, IIIA, and IIIB are written in an explicit step by step fashion in order to familiarize the student with the operation of the test equipment and output signal locations on the control panel. The remaining laboratories in the series rely on the student's accumulated experience to set up the test equipment and obtain the desired experimental results.

LABORATORY I

TITLE

System Familiarization.

OBJECTIVE

Familiarize the student with system connection and operation.

TEST EQUIPMENT REQUIRED

None

SYSTEM EQUIPMENT REQUIRED

Servo amplifier unit
Equipment track with motor and potentiometer
DC input attachment

START-UP CONFIGURATION

1. Prior to performing this or follow-on experiments, place the system in the following startup configuration.

   a. Rotate all potentiometer knobs (black), fully counter-clockwise, (min position). DO NOT adjust the silver knob on the amplifier protective cover.

   b. Position all switches according to the following list:

Switch No.	Name	Startup Position
SW1	AC Power	OFF
SW2	Motor Hold Clamp	ON
SW3	Amp Inhibit	ON
SW4	Forward Clamp	ON
SW5	Reverse Clamp	ON
SW6	Position Feedback	OFF

Switch No.	Name	Startup Position
SW7	Position Feedback Negative/Positive	NEGATIVE
SW8	Velocity Feedback	OFF
SW9	Notch Filter	OUT
SW10	Lead Filter	OUT
SW11	Lag Filter	OUT
SW12	Cascade Compensation	INT
SW13	DC Gain	LOW

2. Connect motor/tachometer and the position potentiometer leads to the system. The leads for these are color coded in three groups of three. Connect the male ends to the corresponding color coded female connector groups.

   Group 1 - MT+, MT-, MT SHLD
   Group 2 - TG+, TG-, TG SHLD
   Group 3 - T22, T23, T24

DISCUSSION

This laboratory experiment covers all the basic features of the Velocity and Position Control Laboratory Servo System. The motor servo will be set up for speed and position control modes of operation. Carefully study the control functions listed below while referring to the Servo System.

Code	Name	Function
		SWITCHES
SW1	AC Power	Supplies AC power to the amplifier, when turned on the fan will start.
SW2	Motor Hold Clamp	ON - The command voltage signal VCS is isolated from the amplifier.
SW3	Amp Inhibit	ON - The amplifier is <u>inactive</u> even if the following two switches are OFF.
SW4	Forward Clamp	ON - Forward side (CCW) of power amplifier is <u>inactive</u> when SW3 is OFF.

Code	Name	Function
SW5	Reverse Clamp	ON - Same as SW4 for reverse or CW side.
SW6	Position Feedback	ON - Position signal sent to summer.
SW7	Position Feedback	Negative - sends a negative feedback signal to Negative/Positive the summing junction.
SW8	Velocity Feedback	ON - Sends a velocity feedback signal to the summer from the tachometer.
SW9	Notch Filter	IN - Places an adjustable notch filter in the velocity feedback channel. OUT - Notch filter is bypassed.
SW10	Lead Filter	IN - Preset lead filter is activated in the velocity feedback channel. OUT - Lead filter inactive, an external compensator can be added.
SW11	Lag Filter	IN - An adjustable lag filter is placed in the forward signal path. OUT - Lag filter bypassed, external compensation can be added.
SW12	Ext. Cascade Compensation	INT - External compensation is bypassed. EXT - Open circuits the preamp signal to allow cascade compensation or sampling in the forward path.
SW13	DC Gain	LOW - Preamp gain ranges from 0.7 to 70. HIGH - Preamp gain ranges from 7 to 700.
		POTENTIOMETERS
P1	Lag Adjust	A 2 Megaohm pot which adjusts the lag time constant (Check description of the lag network for values).
P2	DC Gain Adjust	Varies the DC gain between the values given for SW13 positions.
P3	Signal Attenuator	Varies the signal strength from the preamp to the power amplifier. Min is zero attenuation.
P4	Notch Adjust (R)	Adjustment for Notch Filter,(see Notch Filter description).

Code	Name	Function
P5	Velocity Feedback Attenuator	Adjusts the attenutation of the velocity feedback signal. Used for varying the amount of velocity damping.
P6	Notch Adjust (L)	Adjustment for Notch Filter,(see Notch Filter description).
		Signal/Test Connections
T1	VCS	Terminal for inputting voltage command signals (AC or DC). The Motor Hold Clamp isolates VCS from the amplifier when in the ON position.
T3,T4	External Lag Conn.	A user designed lag network can be added to the circuit at these terminals.
T7,T8	Ext Cascade Compensation	A user designed circuit for the forward path can be added at these terminals
T9,T10	Ext. Lead Filter Conn.	A user designed lead filter for the velocity feedback channel can be added here.
T11	None	Useful for measuring the output of the Notch Filter when in use.
T12	Test	Velocity feedback voltage after the attenuator.
T14	Test	Position feedback voltage
T16	+15 V	Regulated +15 volts, max 50 mA current draw.
T17	-15 V	Regulated -15 volts, max 50 mA current draw.
T19	Test	Forward path voltage, after attenuator.
T22,T23,T24		Position sensor terminal group,match to leads
T25,T26,T27		Tachometer terminal group, match to leads.
T28,T29,T30		DC Motor terminal group, match to leads
T2,T5,T6,T13,T15,T18,T20		Ground connections, all are common.
		Note: The three remaining terminals are located on the right side of the interface panel, below MT+ and MT-.
T31	MVO	Buffered tachometer voltage output. This output will saturate at about 12.5 volts.
T32	MCO	This voltage signal is proportional to the supplied motor current (0.45 volts/amp).
T33	SSO	A DC logic level indicating when the amplifier is active.

PROCEDURE

VELOCITY CONTROL

1. Perform the system balancing procedure described on the last page of this experiment.

2. Install the DC input attachment to T16,T17,T18 DC power terminals.

3. Connect the DC output of the attachment to VCS, set to 0 volts.

4. Turn on the system (SW1).

5. Switch the Forward Clamp and Reverse Clamp OFF.

6. Ensure that the motor and position sensor are uncoupled on the equipment track.

7. Switch Velocity Feedback ON (SW8).

8. Switch Amp Inhibit OFF and Motor Hold Clamp OFF.

   NOTE: If a problem in the system occurs or the system makes unusual noises, switch the Amp Inhibit and/or the Motor Hold Clamp to the ON position.

9. Apply ± DC signals to VCS using the DC Input Attachment. Verify the operation of the Amp Inhibit and Clamp switches.

   NOTE. The system has current limit circuitry. If the small LED indicator lights (located on the amplifier circuit board), reset the system by toggling the Amplifier Inhibit Clamp ON and OFF.

10. Compare qualitatively, the amount of command signal adjustment required to make the motor begin to rotate for low and high gain settings. Use SW13 and P2 in the DC Gain block to vary the gain. Explain what is occuring and why.

POSITION CONTROL

1. Switch Motor Hold Clamp to ON.

2. Switch Velocity Feedback OFF and set DC Gain to the lowest settings (P2 at MIN, SW13 - LOW)

3. Couple the position sensor to the motor.

5. Set Position Feedback (SW6) to ON. Motor will rotate to the zero voltage position.

6. With the command signal set for a positive value (about half way), switch the Motor Hold Clamp OFF and ON to generate step inputs to the system.

7. Observe what happens to the system response as the DC gain is slowly increased. DO NOT switch to the high gain setting. Describe the response.

8. Set the Velocity Feedback Attenuator (P5) to half full value. While generating the step inputs, switch the Velocity Feedback (SW8) ON. Describe the affect on the response. This is known as velocity damping.

9. Turn off the system and restore all controls to the Start-up Configuration.

WRITE-UP

Complete a written report of all observations, results, conclusions, and recommendations.

SYSTEM BALANCING PROCEDURES

1. Place system in the Start-up Configuration.
2. Uncouple position sensor from the motor.
3. Turn on power to system SW1.
4. Switch Forward Clamp, Reverse Clamp, and Amp Inhibit to OFF.
5. With SW13 in the LOW position slowly increase the DC Gain with P2. If the motor begins to rotate, carefully adjust the balance control (silver knob on the amplifier cover) until the motor stops.
6. Continue increasing the gain with P2 and stopping the motor with the balance adjust until P2 is at max. Return P2 to the MIN position and switch SW13 to high gain. Continue as before until MAX is reached on P2 and the motor does not rotate.
7. Switch Amp Inhibit to ON and turn off power to the system.
8. Restore the system to the Start-up Configuration.

LABORATORY II

TITLE

Open Loop Velocity and Position Control

OBJECTIVE

Determine the limitations of open loop speed and position control systems. Measure transient time and time constant of the motor.

TEST EQUIPMENT REQUIRED

Voltmeters (HP 427A)
Pulse/Function Generator (WAVETEK MODEL 145)
Chart Recorder (Gould 220)

SYSTEM EQUIPMENT REQUIRED

Servo amplifier unit
Equipment track with motor and potentiometer
DC input attachment

PRELIMINARY

1. READ the entire procedure prior to performing any steps.

2. The student should familiarize himself with the operation of the voltmeter. A test signal for the voltmeter can be generated by the DC input attachment by placing the system in the Start-Up Configuration (see Experiment I), installing the DC input attachment, and turning on the system (SW1).

3. The student should familiarize himself with the control panel of the Pulse/Function Generator and Chart Recorder. Connect a BNC to two terminal connector on the 50 ohm OUT terminal of the WAVETEK. The input to the Chart recorder is terminal 1, terminal 2 is normally connected to ground.

PROCEDURE

OPEN LOOP VELOCITY CONTROL - BASIC TEST

1. Perform the system balancing procedure described on the last page of Experiment I.

2. Install the DC input attachment to T16,T17,T18 DC power terminals.

3. Connect the DC output of the attachment to VCS, set to 0 volts.

4. Zero both voltmeters and set both voltmeter range scales to maximum scale.

   NOTE: BEFORE ATTEMPTING TO READ A VOLTAGE WITH ANY VOLTMETER, ALWAYS SET THE METER TO ITS HIGHEST RANGE SCALE; THEN SCALE DOWN AS REQUIRED

5. Connect Voltmeter No. 1 to VCS and ground terminal T2 [illegible] read +DCV.

6. Connect Voltmeter No. 2 to T12 and ground te[illegible] to read -DCV.

7. Turn system on (SW1).

8. Adjust the DC input to VCS to zero [illegible]

9. Ensure that the motor and pos[illegible] equipment track

10. Switch the Forwa[illegible] Motor Hold C[illegible]

    NOTE [illegible]

AD-A186 596 DESIGN OF A VELOCITY AND POSITION CONTROL LABORATORY SERVO SYSTEM(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA M A ZIEGLER SEP 87 2/2

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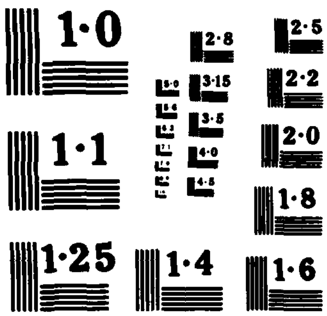
1·0
2·8
2·5
3·15
2·2
3·5
1·1
4·0
2·0
4·5
1·8
1·25
1·4
1·6

NOTE: The system has current limit circuitry, if the small LED indicator lights (located on the amplifier circuit board), reset the system by toggling the Motor Hold and Amplifier Inhibit Clamps ON and then OFF.

11. Rotate input potentiometer to obtain a + voltage. Motor should rotate counterclockwise.

12. Measure the voltage at which the motor just begins to rotate. Record the corresponding tachometer voltage.

13. Vary the command voltage in small increments and record the corresponding tachometer voltage. At what command voltage does the tachometer voltage saturate?

14. From the previous data, is the change in command voltage proportional to the change in tachometer voltage? If it is not, explain.

15. With the command voltage at zero volts, switch voltmeter no. 1 to a -DCV and voltmeter no. 2 to +DCV and reset to zero. Repeat steps 13 through 15 using a negative command voltage. Which direction does the motor rotate?

16. Adjust the command voltage to give about +3 volts output on the tachometer. Slow the motor shaft by hand. Explain the results. Does Open Loop Velocity Control respond well to changes in load?

MEASUREMENT OF TRANSIENT TIME AND TIME CONSTANT

1. Switch SW2 and SW3 ON and turn system power off.

2. Disconnect the DC input from VCS.

3. Connect input no. 1 of the Chart Recorder to VCS and ground and input no. 2 to T12 and ground. Set both sensitivity controls to 1 volt/div.

4. Connect the Pulse/Function Generator to VCS and ground.

5. Set up the function generator as follows:

FREQ/PERIOD	1.0
FREQ KNOB	0.5
ATTENUATION	0 DB, vernier full counterclockwise
FUNCTION	SQUARE PULSE
DC OFFSET	OFF
POWER	ON

6. Turn on the system and switch SW2 and SW3 to OFF.

7. Adjust the output of the Function Generator with the vernier control to an output voltage of at least ±5.0 volts.

8. Set Chart Recorder power to on and set speed to 1. Adjust the position and sensitivity controls to center the recording and allow the pens to travel a minimum of 50% of their full travel.

9. When ready to record, set the Recorder speed to 125, then set to STOP when sufficient data is recorded.

10. Determine the transient time and the time constant.

11. Switch SW2 and SW3 to ON and turn the system OFF. Set Pulse/ Function Generator power to OFF and disconnect it.

OPEN LOOP POSITION CONTROL

1. Connect voltmeter no.1 (set for +DCV), input no. 1 of the Chart Recorder and the DC input attachment output to VCS. Connect grounds on the first two to T2.

2. Connect input no. 2 of the Chart Recorder and voltmeter no. 2 to T14, connect grounds to T15 and set channel 2 sensitivity to 1 volt/div.

3. Couple the position potentiometer to the motor.

4. Turn the system ON and switch SW7 to POSITIVE.

5. Set the DC input to zero volts on voltmeter no. 1.

   NOTE: The motor shaft will stay in a fixed position only if the command signal is 0 volts. You will be attempting to jog the motor shaft into a desired position, which is measured by the potentiometer attached to the shaft.

6. Turn the motor shaft by hand until voltmeter 2 reads zero volts. Then Switch SW2 and SW3 OFF.

7. When ready to record, set the Chart Recorder speed to 1.

8. Adjust the DC input potentiometer slowly until you get a steady 3 volts output on voltmeter no. 2. This may require repeated adjustment of the DC input using + and - DC input voltages, 2 minute time limit.

9. When the position potentiometer is at 3 volts, try to turn the shaft by hand. Explain the result.

10. Switch SW2 and SW3 to ON and turn the system OFF. Restore ALL controls to the Start-up Configuration

11. From the chart record determine the number of command signal changes required to reach the desired output voltage and the time required.

12. What are your conclusions about using an open loop system for position control.

WRITE-UP

Complete a written report of all observations, results, answers, conclusions, and recommendations.

LABORATORY III A

TITLE

Closed Loop Velocity Control - Basics

OBJECTIVE

Determine the characteristics of a closed loop speed control system. Measure the transient time and time constant of a motor with velocity feedback.

TEST EQUIPMENT REQUIRED

Voltmeters (HP 427A)
Pulse/Function Generator (WAVETEK MODEL 145)
Chart Recorder (Gould 220)

SYSTEM EQUIPMENT REQUIRED

Servo amplifier unit
Equipment track with motor and potentiometer
DC input attachment

DISCUSSION

The open loop speed control from Laboratory II can be converted to a closed loop speed control by feeding the tachometer voltage output into the summing amplifier and subtracting it from the input voltage. The difference in these voltages is an ERROR voltage which is a measure of the difference between the commanded speed and motor speed. Calibration of the input command voltage to a motor speed depends on the gain or attentuation in the tachometer feedback channel.

A speed control can never produce exactly the commanded speed, since the ERROR voltage cannat be zero or the motor will not run. Thus, there will always be an errror, however the error can be made small by increasing the amplifier gain.

PRELIMINARY

1. READ the entire procedure prior to performing any steps.

2. Connect a BNC to two terminal connector on the 50 ohm OUT terminal of the Pulse/Function Generator. The input to the Chart recorder is terminal no. 1, terminal no. 2 is normally connected to ground.

3. Connect voltmeter no. 1 to VCS and voltmeter no. 2 to T12. Connect voltmeter grounds to T2 and T13 respectively.

4. "ZERO" both voltmeters and set range scales to 30 volt setting. Set voltmeter no. 1 to +DCV and voltmeter no. 2 to -DCV.

PROCEDURE

CLOSED LOOP VELOCITY CONTROL - BASIC TEST

1. Perform the system balancing procedure described on the last page of Experiment I.

2. Install the DC input attachment to T16,T17,T18 DC power terminals.

3. Connect the DC output of the attachment to VCS, set to 0 volts.

4. Turn system on (SW1).

5. Adjust the DC input to VCS to zero volts on voltmeter no. 1.

6. Ensure that the motor and position sensor are uncoupled.

7. Switch Velocity Feedback (SW8) to ON.

8. Switch the Forward Clamp, Reverse Clamp, Amp Inhibit, and Motor Hold Clamp OFF.

NOTE: If a problem in the system occurs or the system makes unusual noises, switch the Amp Inhibit and/or the Motor Hold Clamp to the ON position.

9. Set the DC input to +2 volts. Motor should rotate CCW.

10. Attempt to slow the motor shaft by hand. Describe the results. How well does a closed loop velocity control respond to changes in load?

11. Record the tachometer voltage and calculate the error voltage for the following gain settings and describe how changes in gain affect the error voltage.

    SW13 - LOW, P2 - MIN
    SW13 - LOW, P2 - Half Max
    SW13 - High, P2 - MIN

12. Set the DC input to zero volts. Switch Amp Inhibit, and Motor Hold Clamp ON and turn the system OFF. Disconnect the DC input from VCS and remove. Set DC Gain to LOW-MIN.

MEASUREMENT OF TIME CONSTANT AND TRANSIENT RESPONSE

1. Connect input no. 1 of the Chart Recorder to VCS and ground and input no. 2 to T12 and ground. Disconnect voltmeter no. 2.

2. Set Chart Recorder power to ON and set speed to 1. Adjust the position controls to center the recording, then set to STOP.

3. Connect the Pulse/Function Generator to VCS and ground. Set up the function generator as follows:

FREQ/PERIOD	0.1
FREQ KNOB	2.0
ATTENUATION	0 DB, vernier full counterclockwise
FUNCTION	SQUARE WAVE
DC OFFSET	OFF

4. Turn on the system and function generator, switch SW2 and SW3 to OFF.

5. Adjust the output of the Function Generator with the vernier control to ±2.0 volts, as indicated by voltmeter no. 1. Adjust the sensitivity of the Chart Recorder channels to prevent the pens from traveling to their stops.

6. When ready to record, set the Recorder speed to 125, then set to STOP when sufficient data is recorded.

7. Determine the transient time.

8. Determine the time constant of the motor.

9. Repeat steps 7 through 10 with the following gain settings:

   SW13 - LOW, P2 - HALF MAX
   SW13 - HIGH, P2 - MIN

10. Switch SW2 and SW3 to ON and turn the system OFF.

11. Set Pulse/Function Generator power to OFF and disconnect it from the system.

12. How does gain affect the transient response and time constant. Explain.

13. Compare this response with open loop results.

14. Restore all controls to the Start-up Configuration.

WRITE-UP

Complete a written report of all observations, results, answers, conclusions, and recommendations.

LABORATORY III B

TITLE

Closed Loop Velocity Control - Open and Closed Loop Transfer Functions

OBJECTIVE

Determine the open and closed loop frequency responses by observing the amplitude and phase versus frequency output of a spectrum analyzer.

TEST EQUIPMENT REQUIRED

HP 3582A Spectrum Analyzer
HP 85 Microcomputer

SYSTEM EQUIPMENT REQUIRED

Servo amplifier unit
Equipment track with motor and potentiometer

PRELIMINARY

1. READ the entire procedure prior to performing any steps.

2. Familiarize yourself with the control panel of the HP 3582A Spectrum Analyzer. The analyzer has two input channels, when used in the transfer function mode, the magnitude and phase of the channel B input divided by the channel A input is displayed.

PROCEDURE

VELOCITY CONTROL - CLOSED LOOP TRANSFER FUNCTION

1. Perform the system balancing procedure described on the last page of Experiment I.

2. Set the HP Spectrum Analyzer control panel to the following settings:

Frequency:	Span - "500 Hz", Mode - "0 start"
Marker:	"ON" - depressed, all others released
Input:	Sensitivity - "+30 V" both channels, Input Mode - "BOTH", Coupling - "sinewave", Isol/Chas - "CHAS"
Trigger:	"FREE RUN", Slope - "+", Repetitive - depressed
Display:	Amplitude - depress "XFR FCTN" (CH A REF), Scale - depress "10 db/div" Phase - depress "XFR FCTN" (CH A REF) COHER - released
Passband:	Shape - depress "FLAT TOP"
Average:	RMS depressed
Number:	Depress "64" and blue button

Noise Source: Random selected and vernier full CCW

3. Perform the following wiring steps. Connect a BNC to two terminal connector on the noise source output. Connect the ground terminals of channels A and B and the noise source to ground on the motor control panel. Connect channel A input and VCS to the noise source output. Connect channel B to the tachometer feedback output at T12. These connections will give us output (velocity) versus input (noise signal).

4. Turn the system on (SW1).

5. Ensure that the motor and position sensor are uncoupled.

6. Switch Velocity Feedback (SW8) to ON and set DC gain to High/Min.

7. Switch the Forward and Reverse Clamps and Amp Inhibit OFF.

   NOTE: If a problem in the system occurs or the system makes unusual noises, switch the Amp Inhibit and/or the Motor Hold Clamp to the <u>ON</u> position.

8. Turn ON the HP Spectrum Analyzer and the HP 85 Computer.

9. Switch the Motor Hold Clamp to OFF and increase the noise source output level, clockwise rotation of vernier, until motor motion can be seen and heard. The sound from the motor should be at or below a normal voice level.

10. Push and release the RESTART button of the Average section on the spectrum analyzer. This restarts data accumulation. When the light above the Trigger control knob goes out, data loading is completed. Use the Amplitude Reference Level to separate the phase and magnitude curves to present a clear display.

11. Once the data loading is completed, switch the Motor Hold Clamp to ON and, tabulate data points from the magnitude and phase versus frequency curves using the marker. Record a sufficient number of points to permit replotting the curves on semi-log paper. The marker can be switched to the phase curve by depressing the TRACE button in the Marker section.

12. A hard copy of the curves displayed on the spectrum analyzer can be obtained from the HP85 computer as follows:

    Type: LOAD "COPY85", then press END LINE, then RUN.
    When asked for grid lines, type: YES, then press END LINE.
    When asked for hard copy, type: YES, then press END LINE.

    Additional copies may be obtained by pressing SHIFT and COPY together. When finished with copying, press the LOCAL button on the analyzer, this restores operation of the control panel.

13. Plot the recorded data on a Bode diagram and smooth data points. Use radian frequencies. The phase curve may require the addition of or subtraction of 180 degrees; use your judgement based on the system type number.

14. Back out the open loop response using a Nichol's Chart, fit asymptotes and write the Open Loop Transfer Function.

VELOCITY CONTROL - OPEN LOOP TRANSFER FUNCTION

1. The open loop transfer function can be obtained when operating a linear system in a closed loop. The system is excited by random noise at VCS, and the output velocity versus the error signal will determine the open loop transfer function.

2. Disconnect channel A from the noise source and connect to terminal T19.

3. Restart data loading and observe the response. Frequency Span should be adjusted so the magnitude curve spans about 20 db.

4. Obtain a hard copy of the response. Record magnitude and phase versus frequency, replot on a Bode diagram, and smooth.

5. Restore the System to the Start-up Configuration.

WRITE-UP

1. Compare the open loop transfer functions obtained by the two methods. Explain any differences.

2. How might one measure the forward path gain using the spectrum analyzer? Illustrate with a basic block diagram of the system and the required connections.

3. Draw the transfer function block diagram. Use this to write a simulation program (DSL) and verify the simulations frequency response with the experimental results. Simulate the step response and compare with the results of Lab III A.

4. Describe an alternate method of obtaining the system's frequency response with available equipment, but not the spectrum analyzer.

5. Complete a written report of all observations, results, answers, conclusions, and recommendations.

LABORATORY IV A

TITLE

CLosed Loop Position Control - Basics and Transfer Functions

OBJECTIVE

Determine the characteristics of a closed loop position control system. Measure the settling time, time constant, and frequency response of the system in a position control mode.

TEST EQUIPMENT REQUIRED

Voltmeters (HP 427A)
Pulse/Function Generator (WAVETEK MODEL 145)
Chart Recorder (Gould 220)
HP 85 Microcomputer
HP 3582A Spectrum Analyzer

SYSTEM EQUIPMENT REQUIRED

Servo amplifier unit
Equipment track with motor and potentiometer
DC input attachment

DISCUSSION

The open loop position control from Laboratory II can be converted to a closed loop position control by feeding the position sensor voltage output into the summing amplifier and subtracting it from the input voltage. The difference in these voltages is an ERROR signal which causes the motor to rotate to reduce the error.

A position control will have no error to a step input, because if an error does exist the motor will rotate to reduce it to zero. Calibration of the input voltage to a shaft position depends on the gain used in the position sensor, volts/radian.

PRELIMINARY

1. READ the entire procedure prior to performing any steps.

2. As stated in the preface to this experimental series the procedural steps which follow will be limited in their detail. The student should rely on past laboratory procedures. If in doubt about the steps to take ask the instructor.

PROCEDURE

CLOSED LOOP POSITION CONTROL - BASIC TEST

1. Perform the system balancing procedure described on the last page of Experiment I.

2. Couple the position potentiometer to the motor shaft.

3. Switch Position Feedback (SW6) to ON. Velocity Feedback (SW8) should remain OFF during this experiment.

4. Using DC voltage input commands, determine the direction of shaft rotation for positive and negative inputs.

5. Vary the forward path gain and describe the effect on system stability. DO NOT set the DC Gain to the HIGH setting. Use the Motor Hold Clamp to generate step inputs.

6. Determine the effect of an external load on shaft position.

MEASUREMENT OF THE TIME CONSTANT AND SETTLING TIME

1. Using the Chart Recorder and signal generator, measure the step response of the system with position as the output. Use a low gain and step voltage setting.

2. Based on the results of the step response, can this system be characterized by a time constant? Explain your reasoning.

3. From the chart record, determine the system settling time.

POSITION CONTROL - CLOSED LOOP TRANSFER FUNCTION

1. Set the HP Spectrum Analyzer control panel to the settings used in Laboratory IIIB.

2. Obtain the closed loop frequency response on the spectrum analyzer display with position as the output. The Frequency Span may need adjustment to obtain an adequate display. Tabulate data from the curves for transfer to a Bode plot and obtain a hard copy of the display.

3. Construct a Bode diagram of the closed and open loop frequency response. Determine the open loop transfer function.

POSITION CONTROL - OPEN LOOP TRANSFER FUNCTION

1. Obtain the open loop frequency response directly with the spectrum analyzer, position versus the error signal.

2. Obtain a hard copy of the response. Record magnitude and phase versus frequency and plot on a Bode diagram.

3. Restore the System to the Start-up Configuration.

WRITE-UP

1. Draw a simple block diagram of the connections made between the control panel and test equipment for each of the measurements taken.

2. Compare the open loop transfer functions obtained by the two methods. Explain any differences.

3. Complete a written report of all observations, results, answers, conclusions, and recommendations.

LABORATORY IV B

TITLE

CLosed Loop Position Control - Velocity Damping

OBJECTIVE

Demonstrate using velocity feedback to damp the behavior of a position control system. Determine the effect of forward and feedback gain variations on this system control mode.

TEST EQUIPMENT REQUIRED

Voltmeters (HP 427A)
Pulse/Function Generator (WAVETEK MODEL 145)
Chart Recorder (Gould 220)

SYSTEM EQUIPMENT REQUIRED

Servo amplifier unit
Equipment track with motor and potentiometer

DISCUSSION

There are several methods of stabilizing a control system, one of these is to feed back a velocity signal to the error detector (summing junction). This is described as velocity feedback damping.

You discovered in Laboratory IV A that, with the system in a closed loop position control mode, a slight increase in forward path gain would cause the system to become unstable. Additionally, the step response showed considerable overshoot and ocsillation. This lab will demonstrate the stabilizing effect that velocity damping has on the position control system.

PRELIMINARY

1. <u>READ</u> the entire procedure prior to performing any steps.

PROCEDURE

CLOSED LOOP POSITION CONTROL WITH VELOCITY FEEDBACK

1. Perform the system balancing procedure described on the last page of Experiment I.

2. Couple the position potentiometer to the motor shaft. Align the system for position control with velocity feedback and set the velocity feedback attenuation to 1/2.

3. Switch the Motor Hold Clamp to ON, set DC gain to HIGH/MIN. Determine how the position system responds to external loads.

4. Using a square wave input, observe the position output on the chart recorder. Limit the input signal to ±1.0 volts and 1 Hz.

5. Record the position output for all the combinations of DC gain and velocity feedback attenuation using 1/2 turn increments for the potentiometers and both high and low gain settings. Describe the effect forward gain and feedback gain have on the system, with respect to overshoot, settling time, rise time and the system time constant.

6. Set the DC gain to HIGH/MIN and adjust the velocity feedback attentuator from the full setting toward 0 until no overshoot or oscillation occurs. For a second order system, what is the numerical value of the damping ratio ξ corresponding to this response?

WRITE-UP

1. Draw a simple block diagram of the connections made between the control panel and test equipment for each of the measurements taken.

2. Complete a written report of all observations, results, answers, conclusions, and recommendations.

APPENDIX E

PREFACE TO EXAMPLE LABORATORY REPORTS

The laboratory reports enclosed in this Appendix are intended to aid the instructor in the conduct and grading of student laboratory reports. The lab procedures of Appendix D were conducted on the actual system with the results described in the reports. The answers and conclusions given in the reports are more complete than one would expect from the beginning student. Items indicated with an asterik are notes intended for the instructor.

LABORATORY I REPORT

TITLE : SYSTEM FAMILIARIZATION

PURPOSE : Gain familiarity with the Velocity and Position Servo Control System.

DISCUSSION : This lab describes all control and test functions of the control panel, the start-up configuration for the system and qualitatively studies closed loop velocity and position feedback system operation.

RESULTS :

Velocity Control - The system was placed in a closed loop velocity control mode, the following data and results were obtained in accordance with the procedure:

Step 9: Operation of the Amp Inhibit and Clamp switches.

All clamps and the inhibit switch are disabled in the OFF position. The following statements describe the operation of the switches when ON. The Amplifier Inhibit switch disables the output drivers causing the motor to freewheel to a stop. The Forward Clamp disables the counterclockwise output drivers, the Amp Inhibit must be OFF. The Reverse Clamp operates like the Forward Clamp

for clockwise motion. The Motor Hold Clamp open circuits the input command VCS and grounds the summer input causing the motor to brake to a stop using reverse current (does not freewheel to a stop).

Step 10: Effect of gain upon the voltage required to start rotating the motor.

As the gain is increased the amount of DC voltage (device adjustment) required to start the motor decreases. The increased gain allows a smaller error signal, between the input command and motor tachometer voltage, to overcome the static friction in the motor. Thus the motor will rotate for a smaller input.

Position Control - The system was placed in a closed loop position control mode of operation. Velocity feedback damping was added to determine its effect on system response.

Step 7: Effect of DC gain on system response.

The DC gain was slowly increased from the LOW-MIN position. This caused the motor step response to become increasingly oscillatory with longer settling time. At a DC gain of LOW-2/3 MAX the system became unstable and oscillated continuously.

Step 8: Effect of velocity damping on system response.

When velocity damping is added, the oscillations of the step response are almost eliminated and the system settles quickly.

CONCLUSIONS: The following statements summarize the results of the lab. The control panel clamps operate as indicated in the lab discussion section. The amount of error between input command and motor speed of the velocity control system depends on the forward gain of the system. The position control mode with no damping is highly oscillatory and will become unstable if the gain is raised too high. Velocity damping provides a means of stabilizing the position control mode of operation.

RECOMMENDATIONS AND COMMENTS : * The student should indicate any problems encountered with the lab procedures or equipment and comment on the value of the lab as a learning tool.

LABORATORY II REPORT

TITLE : OPEN LOOP VELOCITY AND POSITION CONTROL

PURPOSE : Determine the limitations of operating a servo system in an open loop velocity or position control mode and measure the time constant and transient time of the motor. * This lab is also intended to familiarize the student with the operation of test equipment.

DISCUSSION : The limitations of open loop systems is explored by applying input commands to the system and measuring its response with voltmeters and a chart recorder. The time constant and transient time is determined from the chart record.

RESULTS :

Open Loop Velocity Control - Basic Test - The system was placed in an open loop velocity control mode (no feedback) and DC voltages applied to the input VCS with the DC Input Attachment.

Steps 12-15: Command Voltage versus Tachometer Voltage.

The motor begins to rotate CCW at an input voltage of +0.50 volts, giving a tachometer output voltage of -0.2 volts and CW with +0.48 volts input giving -0.8 volts tachometer output. The variation

of tachometer voltage with input voltage is shown in Table A. As can be seen from the voltage ratio column the tachometer voltage does not vary proportionally to the input voltage for either rotation. This is due to the lack of a feedback signal telling the system how the voltage being sent to the motor changes its velocity. The tachometer voltage saturates at -17.4 volts with an input command of +0.63 volts and +17.4 volts with -0.58 volts input. The differences between the forward CCW and reverse CW rotation voltages is due to small differences in the output driver circuitry.

TABLE A

TACHOMETER VOLTAGE VERSUS INPUT COMMAND

Input Command Voltage	Tachometer Voltage	Tach V/Input
	Counterclockwise Rotation	
+0.50	-0.20 Motor Starts	0.4
+0.52	-1.45	2.8
+0.54	-3.8	7.0
+0.55	-5.5	10.0
+0.57	-9.5	16.6
+0.60	-16.5	27.5
+0.63	-17.4 Saturation	27.6
	Clockwise Rotation	
-0.48	+0.8	1.7
-0.50	+0.95	1.9
-0.52	+5.5	10.6
-0.54	+9.7	18.0
-0.56	+14.0	25.0
-0.58	+17.4 Saturation	30.0

Step 16: External Load on an Open Loop Velocity Control.

The command input was adjusted to give +3.0 volts output on the tachometer. The shaft could be slowed to a stop by hand. Thus an open loop velocity control cannot respond to changes in external loads. Because a velocity indication is not feed back, it cannot correct the difference between the actual and commanded speeds.

Measurement of Transient Time and Time Constant - The system is configured for open loop velocity control using a function generator as input through VCS and recording the input signal and output tachometer voltage on two separate channels of a chart recorder.

Step 9: Measurement of Step Response.

The chart recorder output of the open loop step response is shown in Figure A, using a square wave from the function generator.

Step 10: Determination of time constant and transient time.

If the step response is assumed exponential, then the time constant of the system is determined as the time taken to reach approximately 63% of the final speed. From Figure A, the time constant is approximately 112 msec, and the transient time to within 2% of final value is 250 msec.

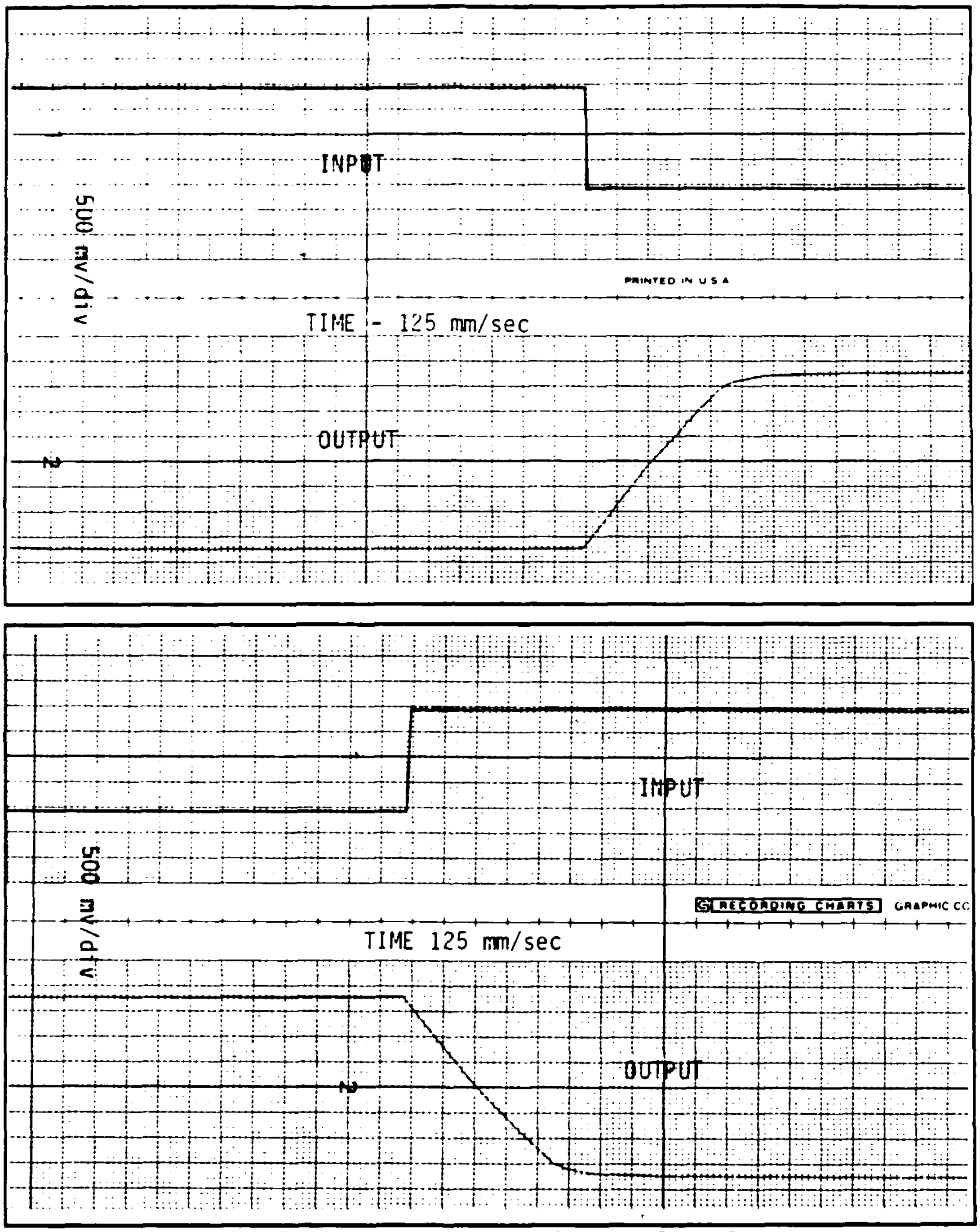

Figure A. Open Loop Velocity Control Step Response
Upper - ±6 Volt Step Positive Transition
Lower - ±6 Volt Step Negative Transition

* The actual motor time constant is smaller than what the student measures in this lab. The setting of the peak current limit at 3.5 amps makes the motor responds more slowly giving the response shown, which is clearly not exponential. However, determining the time constant from experimental data is a useful exercise for the student.

Open Loop Position Control - The position potentiometer was coupled to the motor shaft and shaft position was determined by the output voltage of the potentiometer.

Step 8: Driving the motor shaft to a desired position.

DC inputs were given to the system to bring the motor to a position indicated by a voltage of +3 volts from the position sensor. Figure B is the record of the commands given and shaft position.

Step 9: Effect of external load on the open loop system.

The shaft could be rotated by hand after being positioned at 3 volts. This indicates that the open loop position control system cannot correct for changes in load. Additionally, if the initial conditions were different than the 0 volts used and the same command input was used, the final position would be different.

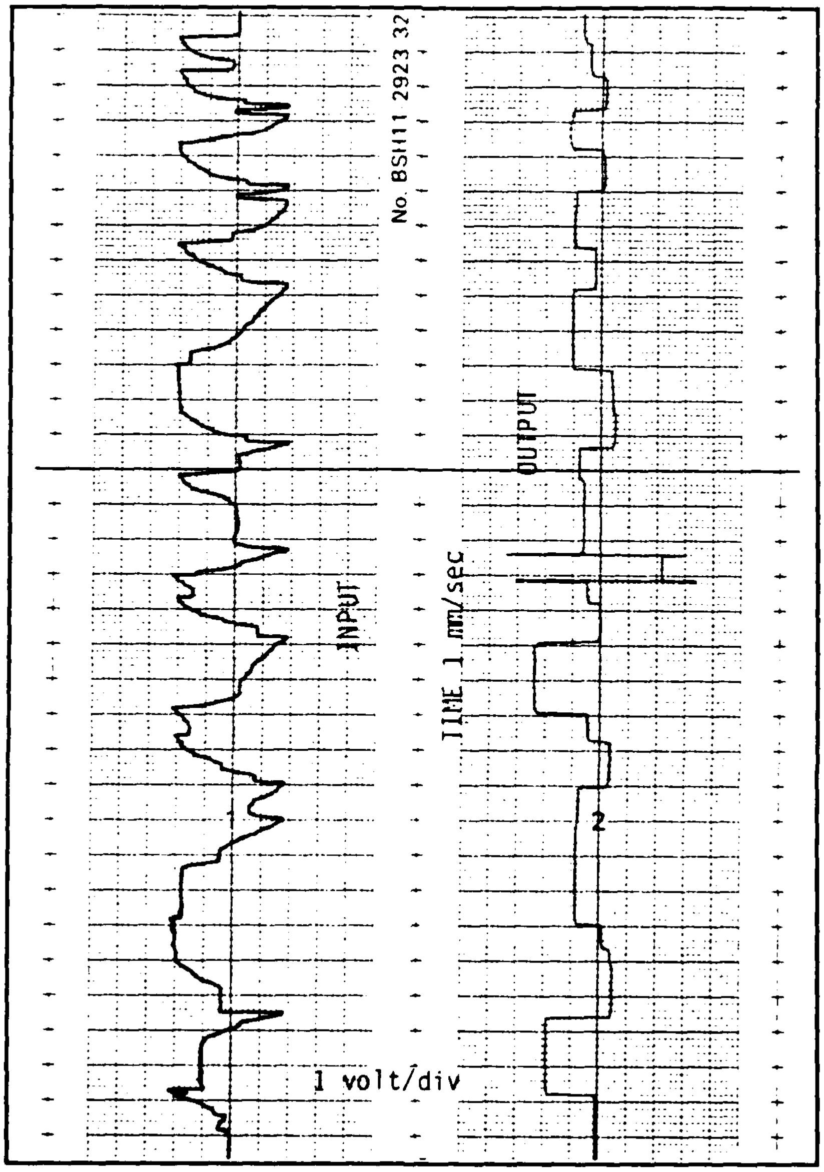

Figure B. Open Loop Position Test

Step 11: Open loop position test results.

Total time to reach the desired position was 2 min 37 sec. There were about 28 different commands given to reach the final +3 volts.

CONCLUSIONS : The use of an open loop system for velocity or position control is very unsatisfactory if accuracy is required in the application. Open Loop Velocity Control could be used if the speed of the motor need not remain constant in normal operation and with variations in load. Most applications for a position control system require accurate positioning. Some type of position feedback is therefore needed to keep the motor positioned correctly for changes in load and initial conditions.

RECOMMENDATIONS : *Student comments.

LABORATORY III A REPORT

TITLE : CLOSED LOOP VELOCITY CONTROL - BASICS

PURPOSE : Analyze a closed loop velocity control system with respect to forward gain, and determine the system's time constant and transient time.

DISCUSSION : The open loop velocity control system of Laboratory II was converted to a closed loop system by feeding back the tachometer output voltage into a summer and subtracting it from the input command voltage. The output of the summer, called the error voltage, cannot be zero or the motor will not run. The effect of forward gain on this error is to be examined in the lab.

RESULTS :

Basic Test - Measurements were taken to determine the effect of gain on the error voltage and speed changes with load.

Step 10: An external load was applied to the motor by hand. The speed slowed only slightly, indicating that a closed loop velocity control responds well to changes in load.

Step 11: Measurement of the error voltage with varying gain and an input command of +2.0 volts gave the following results.

Gain	Tachometer Voltage (V)	Error (V)
LOW-MIN	-1.5	0.5
LOW-1/2	-1.76	0.24
HIGH-MIN	-1.96	0.04

Step 12: Since a velocity control is a type zero system the steady state error is given by; $E_{SS} = 1/(1 + K)$, where K is the system's forward gain and is proportional to the amplifier gain. The results and theory agree that raising gain, decreases the error.

Measurement of Transient Time and Time Constant - The chart recorder was connected to the system with input 1 measuring the command signal VCS and input 2 to the tachometer output. The signal generator was connected to VCS and set to provide step input commands of ± 2 volts.

Steps 6-9: The step responses generated by the system are shown in Figures A, B, and C for the indicated gain settings. From the records the following values for time constant and transient response were found.

Gain	Time Constant	Transient Time
LOW-MIN	12 msec	44 msec
LOW-1/2	12 msec	32 msec
HIGH-MIN	12 msec	24 msec

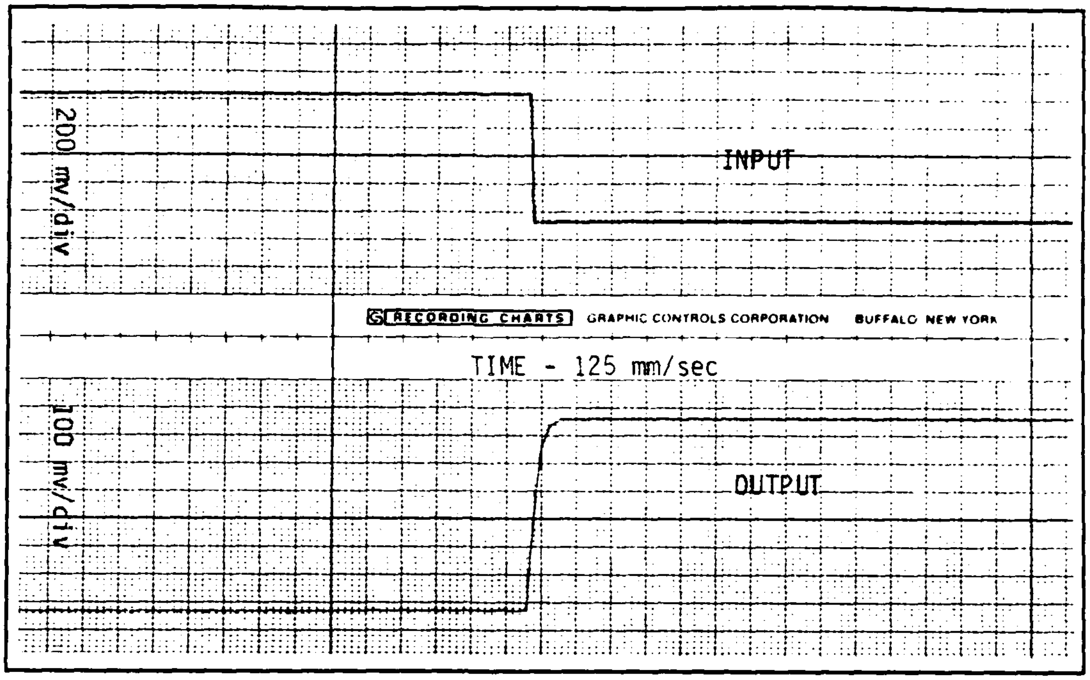

Figure A Closed Loop Step Response - Gain Setting LOW - MIN

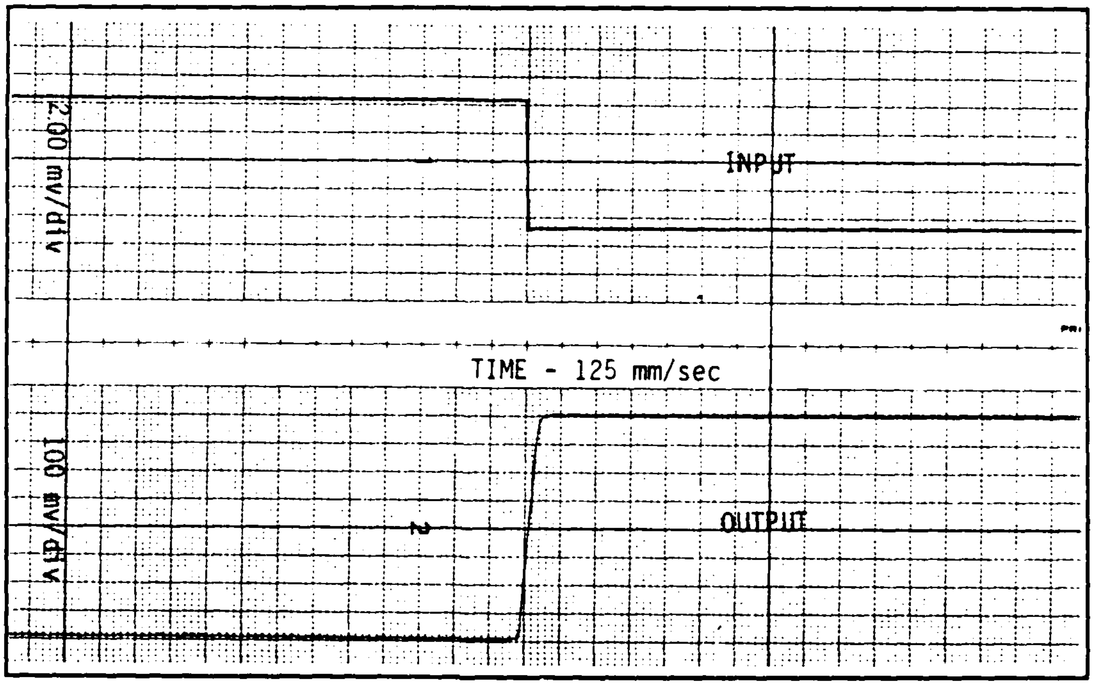

Figure B Closed Loop Step Response - Gain Setting LOW - 1/2

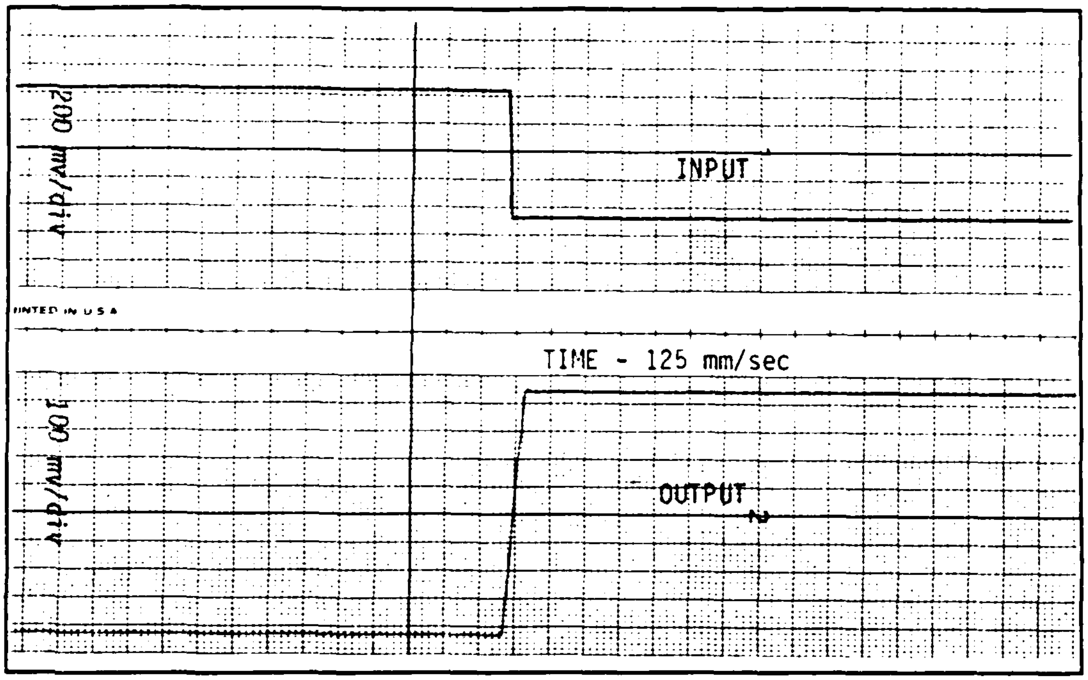

Figure C Closed Loop Step Response - Gain Setting HIGH - MIN

* The chart recorder used has insufficient bandwidth to give accurate measurements of the system time constant.

Steps 12 and 13: The gain does show an affect on the transient time. Because of the speed of the system the record does not show a variation in the time constant. From theory, the open loop transfer function of a system characterized by a time constant is:

$G(s) = k/(s\tau + 1)$, where k is the system gain and τ is the time constant. For an open loop system the gain will have no effect

on the system's time constant. In the closed loop mode the transfer function is given by:

$$G_{cl}(s) = G(s)/[\,1 + G(s)] = k/\,(s\tau + 1 + k)$$

this can be rearranged to give:

$$G_{cl}(s) = \frac{k/(1 + k)}{\left(s \frac{\tau}{1 + k} + 1\right)}$$

The closed loop time constant is $\tau/(1 + k)$. Therefore as gain is increased the time constant will decrease. The transient time is directly related to the time constant, for a larger time constant one obtains a larger transient time. The results show a decrease of transient time with increase in gain, which adds validity to the assumption that the recorder is unable to measure the time constant accurately. In accordance with theory, the open loop time constant from Lab II of 112 msec is considerably larger than the closed loop.

CONCLUSIONS: The response of the closed loop velocity control system to changes in gain agreed with theory. The closed loop system responds well to changes in load. The amount of error between the input command velocity and the motor velocity can be reduced by increasing the gain.

RECOMMENDATIONS AND COMMENTS: * Student comments.

LABORATORY III B REPORT

TITLE: CLOSED LOOP VELOCITY CONTROL - FREQUENCY RESPONSE

PURPOSE: Measure the frequency response of the closed loop velocity control system using a spectrum analyzer and determine the open and closed loop transfer functions.

DISCUSSION: The system was set up for operation as a closed loop velocity control with the spectrum analyzer noise generator as input to VCS and the tachometer voltage as output to the analyzer.

RESULTS:

Closed Loop Frequence Response

Steps 11 and 12: The spectrum analyzer results are shown in Figure A. Data points for magnitude and phase were tabulated from the curves using the spectrum analyzer marker. *For brevity the data point tabulation is not included here.

Step 14: Using the tabulated data, with frequencies adjusted to radians/sec, the closed loop Bode diagram is obtained, see Figure B.

Step 15: The closed loop data was transferred to the M and N curves of a Nichol's chart, then using the x and y coordinate scales,

the open loop magnitude and phase was plotted on another Bode diagram, * plot was done freehand and not included here. The value of DC gain could not be obtained from the Nichol's chart, but it can be calculated from the DC closed loop magnitude of -2.4 db. The equation for a closed loop velocity control system can be written as:

$$G_{cl}(s) = K/[\ (s/p_1 + 1\ )(s/p_2 + 1\ ) + K]\ ,$$

where K is the Bode gain and p_1 and p_2 are the system poles. At DC, s = 0, and the closed loop gain is K/(1 + K). Solving for K and using the -2.4 db, one obtains a DC gain of 3.14 or +9.9 db.

By fitting asymptotes of -20 and -40 db/decade to the data and using the DC gain calculated, an approximation for the open loop transfer function can be written as:

$$G_{ol}(s) = \frac{3.14}{\left(\frac{s}{150} + 1\right)\left(\frac{s}{1250} + 1\right)}$$

<u>Open Loop Frequency Response</u> - The open loop response was obtain while in the closed loop control mode by exciting the system with noise at VCS and measuring the magnitude and phase of the tachometer output with respect to the output of the summer.

Step 4: The spectrum analyzer results are shown in Figure C. Data points for magnitude and phase were tabulated from the curves using the spectrum analyzer marker. *For brevity the data point tabulation is not included here. The data was plotted on a Bode diagram, Figure D.

Using asymptotes and assuming a gain K, the open loop transfer function is:

$$G_{ol}(s) = \frac{K}{\left(\frac{s}{200} + 1\right)\left(\frac{s}{1600} + 1\right)}$$

CONCLUSIONS:

1. The open loop transfer functions, obtain by the two methods, differ in the values of the poles. The difference is not very significant when one looks at the step response found when simulating the transfer functions and using K = 3.14.

2. The spectrum analyzer can be used to find the forward path gain as follows: With the system in a closed loop velocity configuration and no input to VCS, channel A is connected to the noise source, the noise source is connected into the velocity feedback test point T12, and channel B is connected to the system at T19 in the forward path. * Block Diagram omitted.

3. The transfer functions were inputted to a frequency response and simulation program to compare the data generated curves with the estimated transfer functions. Figures E and F are the closed and open loop response from method one's transfer function. Comparison with the data plots shows good agreement.

The step response was simulated with the two transfer functions, shown in Figures G and H. These were compared to each other and the responses obtained in Laboratory III A. Again the data agrees with both simulations. * Block diagram omitted, see body of thesis, chapter II.

4. The frequency response of the system can also be measured by inputting sinusiodal signals from the function generator and recording the output on the chart recorder. The magnitude and phase variations with frequency can be determined from the chart records and plotted.

<u>RECOMMENDATIONS AND COMMENTS</u>: * Student comments.

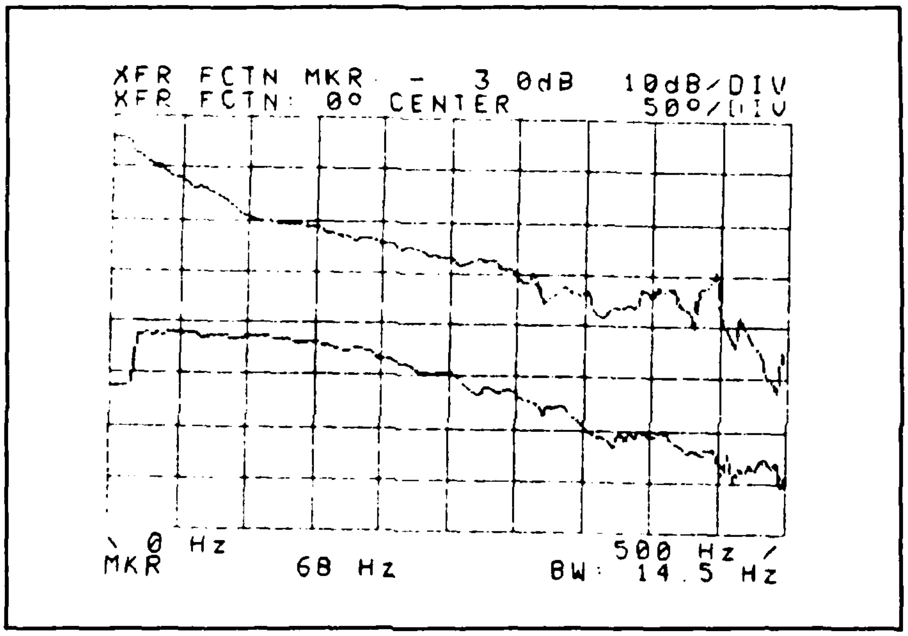

Figure A. Spectrum Analyzer Closed Loop Output

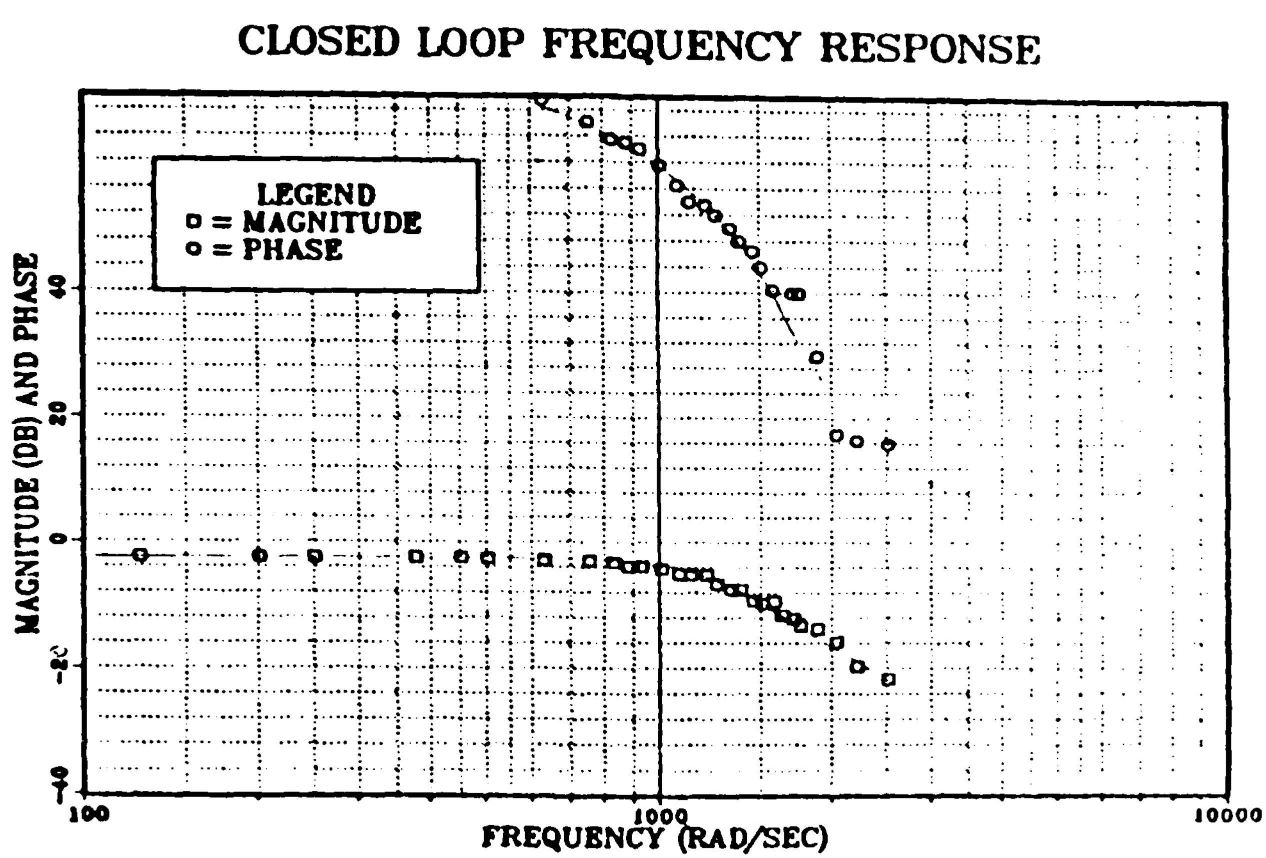

Figure B. Bode Plot of Spectrum Analyzer Closed Loop Data

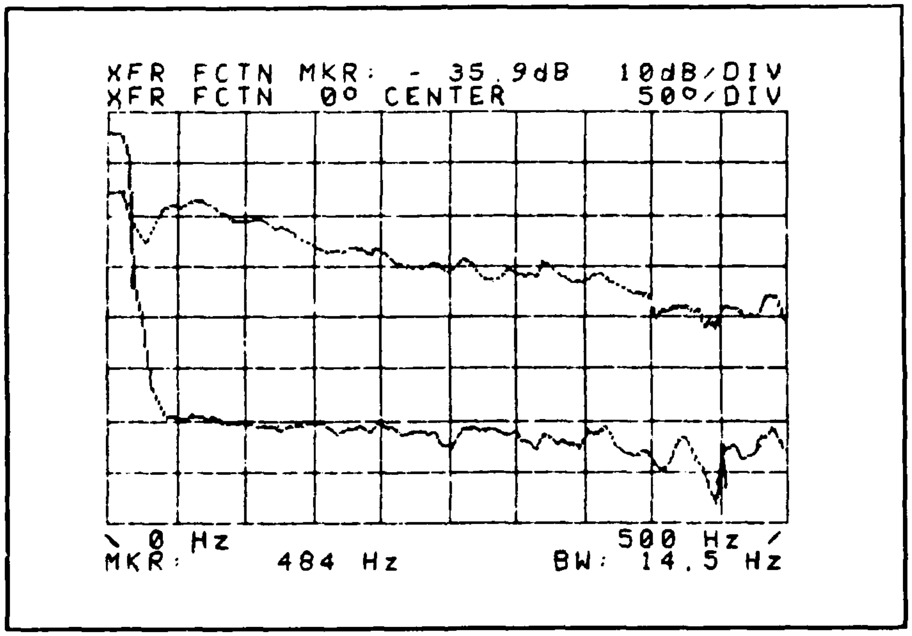

Figure C. Spectrum Analyzer Open Loop Output

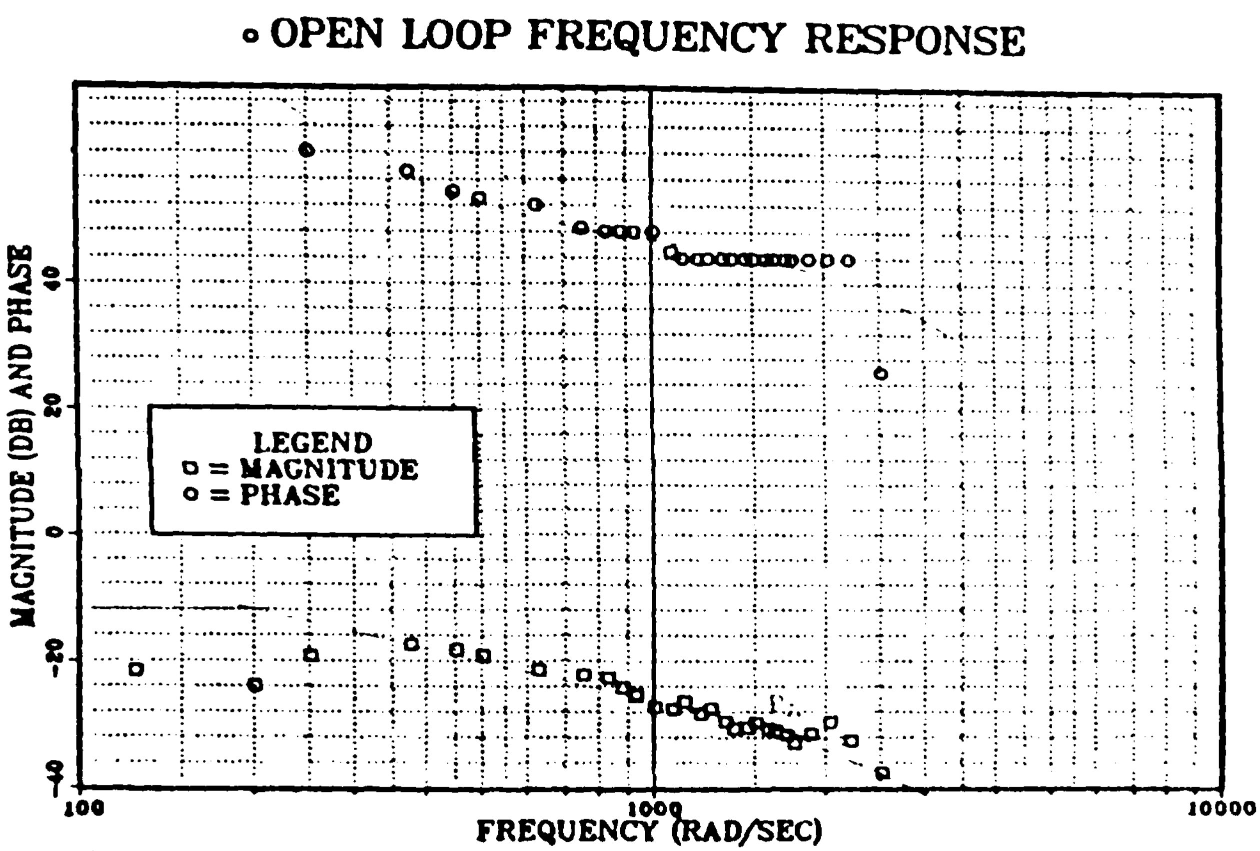

Figure D. Bode Plot of Spectrum Analyzer Open Loop Data

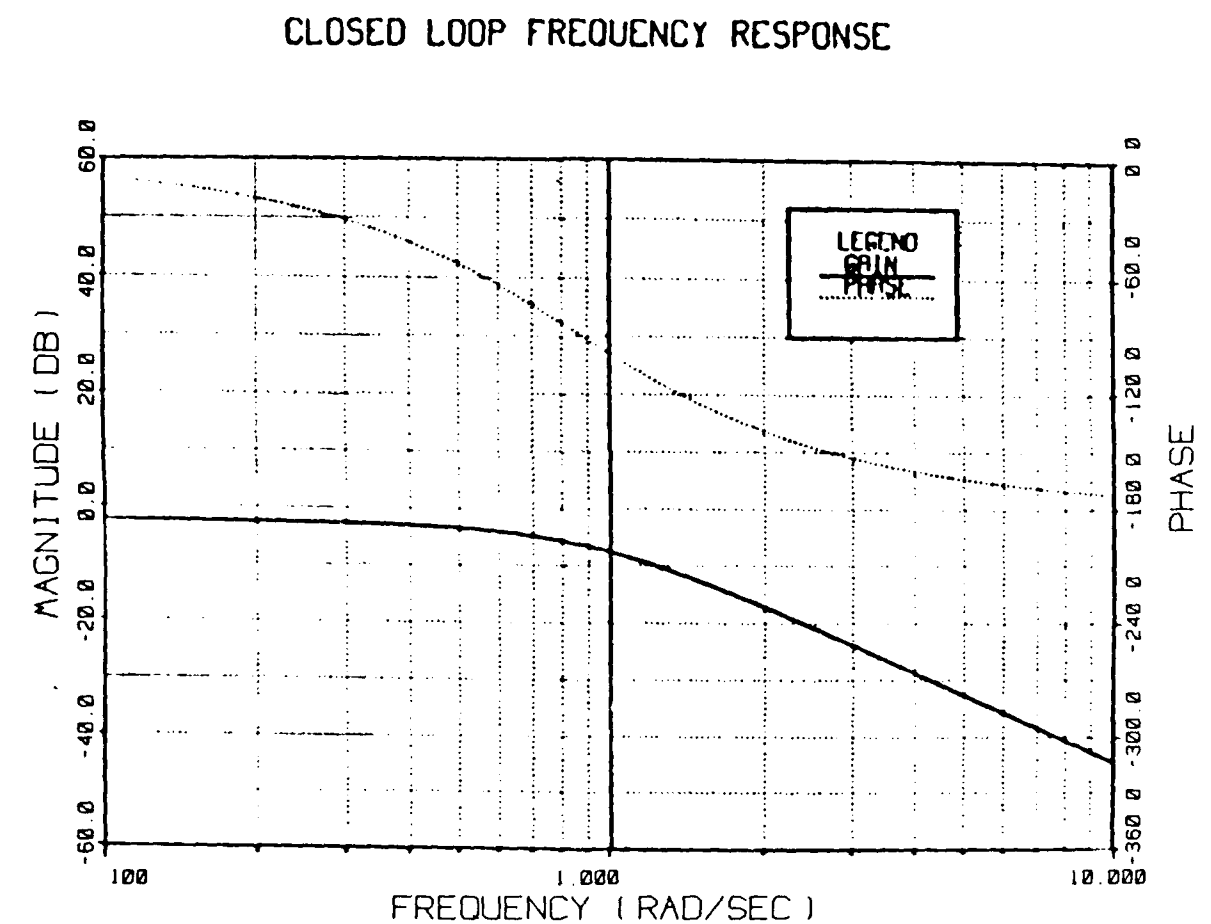

Figure E. Closed Loop Frequency Response Simulation from Transfer Function 1.

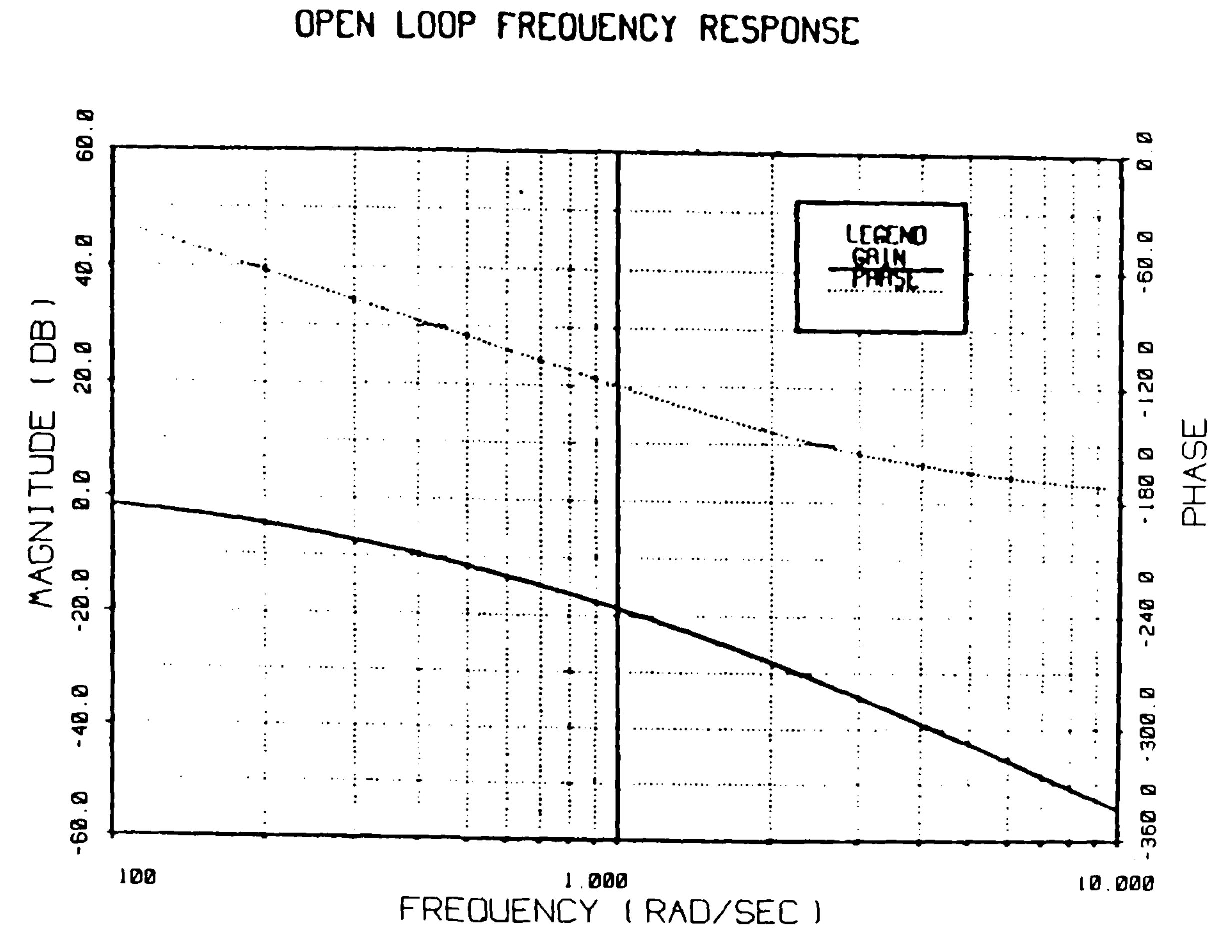

Figure F. Open Loop Frequency Response Simulation from Transfer Function 1.

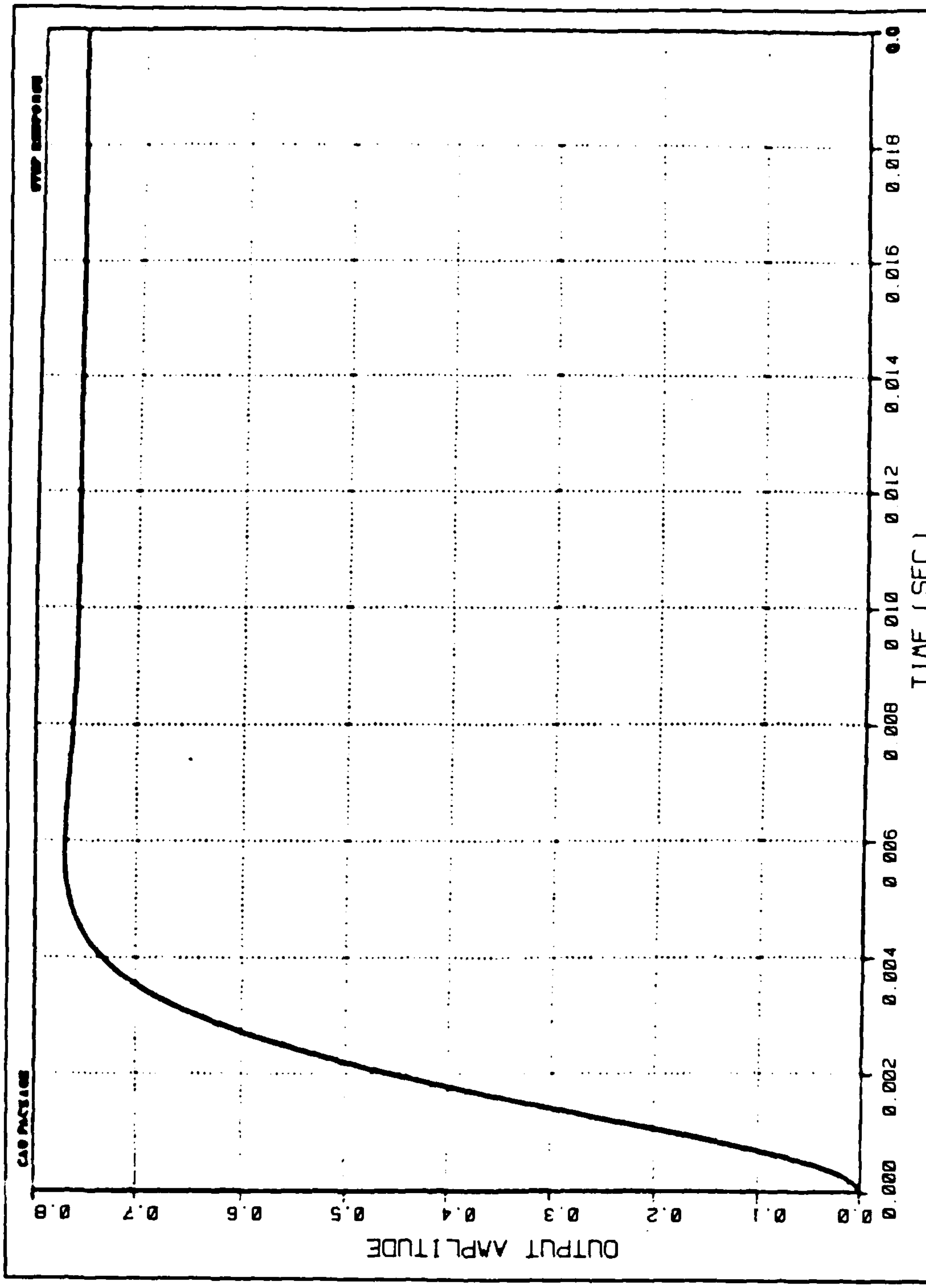

Figure G. Step Response Simulation using Transfer Function 1.

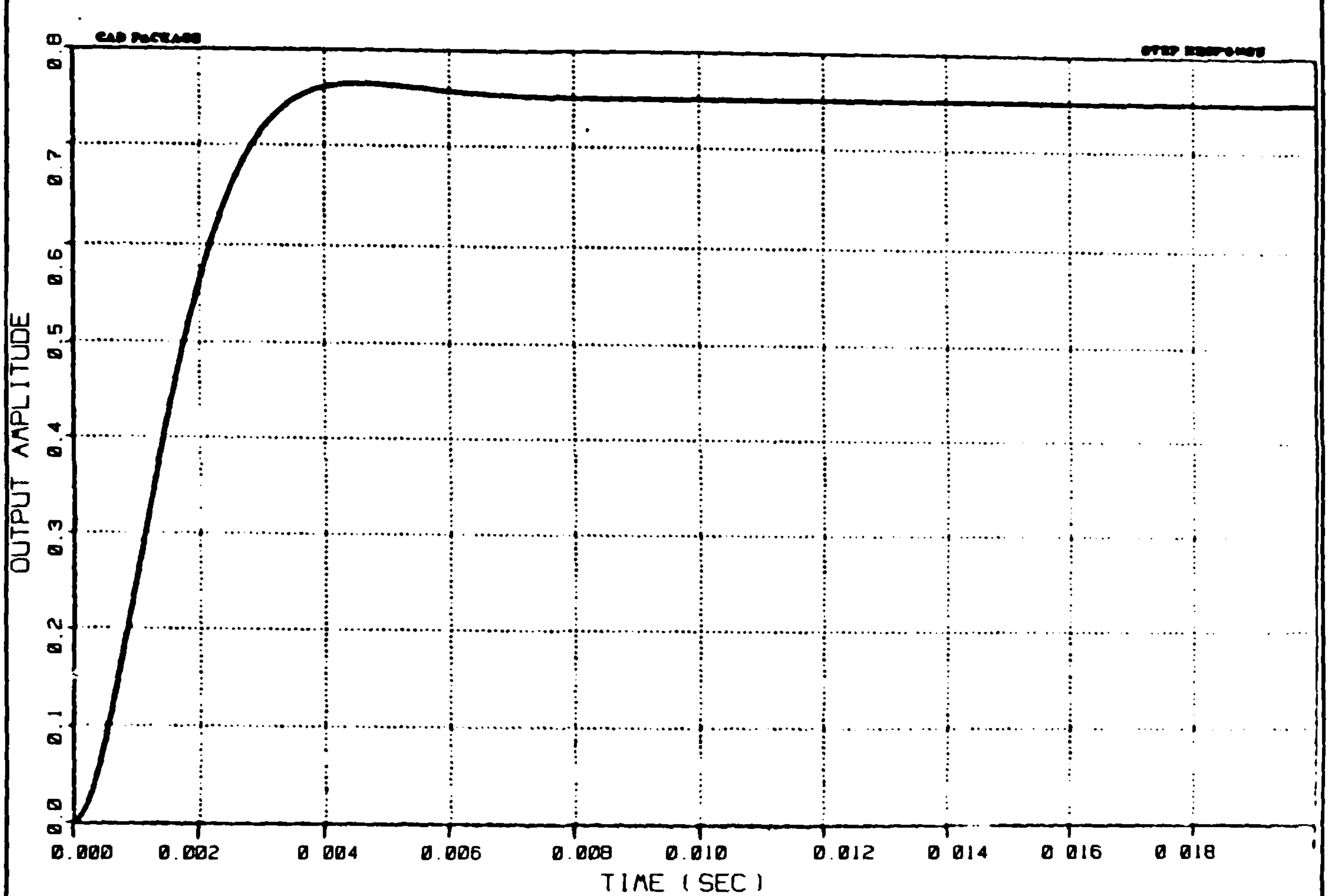

Figure H. Step Response Simulation using Transfer Function 2.

LABORATORY IV A REPORT

TITLE: CLOSED LOOP POSITON CONTROL - BASICS AND TRANSFER FUNCTIONS

PURPOSE: Measure the following characteristics of a closed loop position control system; settling time, time constant, and open and closed loop frequency response.

DISCUSSION: The open loop position control system from Lab II was converted to a closed loop system by feeding back the output voltage of a potentiometer coupled to the motor shaft. The effects of gain on system response are studied and the open and closed loop transfer functions are measured with a spectrum analyzer.

RESULTS:

Basic Test - The system was placed in a closed loop position control mode and subject to DC input commands while varing DC gain.

Step 4: Motor shaft position movement is counterclockwise from the zero position for positive inputs and clockwise for negative.

Step 5: The DC gain of the system was slowly increased while generating step inputs to the system using the DC input device and switching the Motor Hold Clamp ON and OFF. Raising the gain caused

the response became increasingly oscillatory. When the gain setting reached LOW-2/3 MAX, the system became unstable and oscillated continuously. Increasing gain also lengthened the settling time.

Step 6: An external load was applied to the motor shaft by hand. The amount of movement of the shaft was minimal and decreased as the gain was raised. Thus, the closed loop position system can react well to external load disturbances with minimal position error.

<u>Measurement of Time Constant and Settling Time</u> - The closed loop position system was setup to measure the step response as follows: The output of the Function Generator was connected to the system at VCS, channel 1 of the chart recorder was connected to VCS and channel 2 to position test point T14.

Step 1: A square wave of ±2 volts was applied to the system and the response measured by the recorder, for a gain of LOW-MIN.

Step 2: The closed loop response of the position control system, Figure A, cannot be characterized by a single time constant. The response has an overshoot indicating the characteristic equation has complex roots and therefore is described by a second order equation.

Step 3: The settling time for the response is about 64 msec.

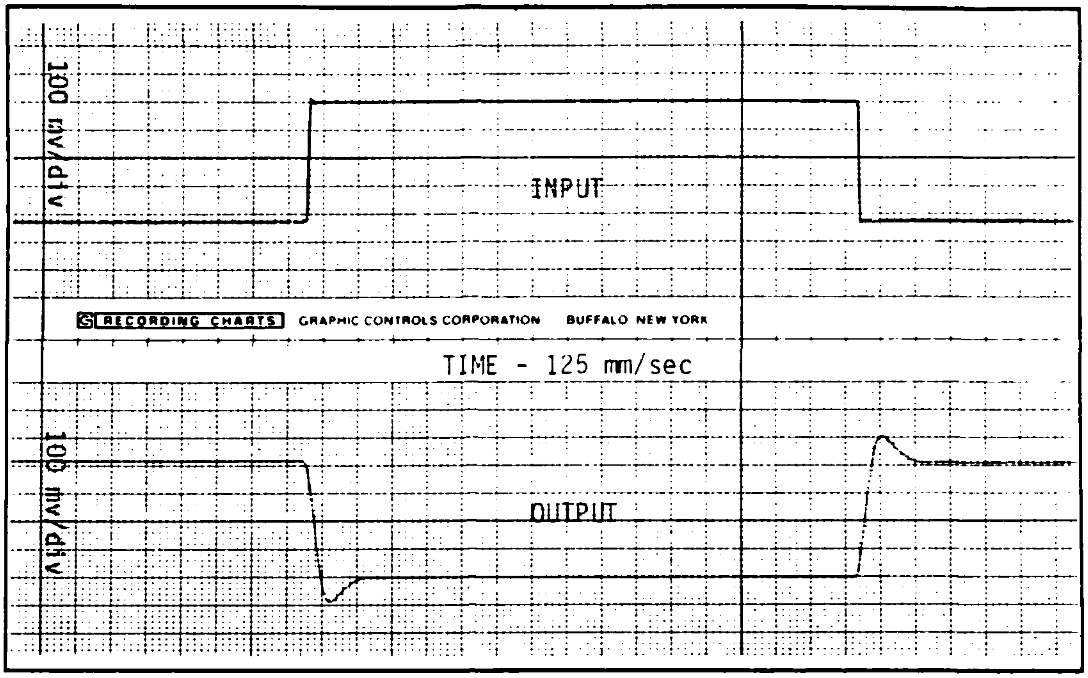

Figure A. Step Response of the Position Control System

Closed Loop Transfer Function - The closed loop frequency response was measured using the spectrum analyzer with the settings of Lab III B except the frequency span was set to 50 Hz. The analyzer was connected to the system as follows: The noise generator output was connected to VCS and channel A input, channel B input was connected to position test point T14. All channels were properly grounded.

System gain was kept at LOW-MIN throughout the measurement. The results from the analyzer is shown in Figure B. Data points were tabulated and plotted on a Bode Diagram, Figure C.

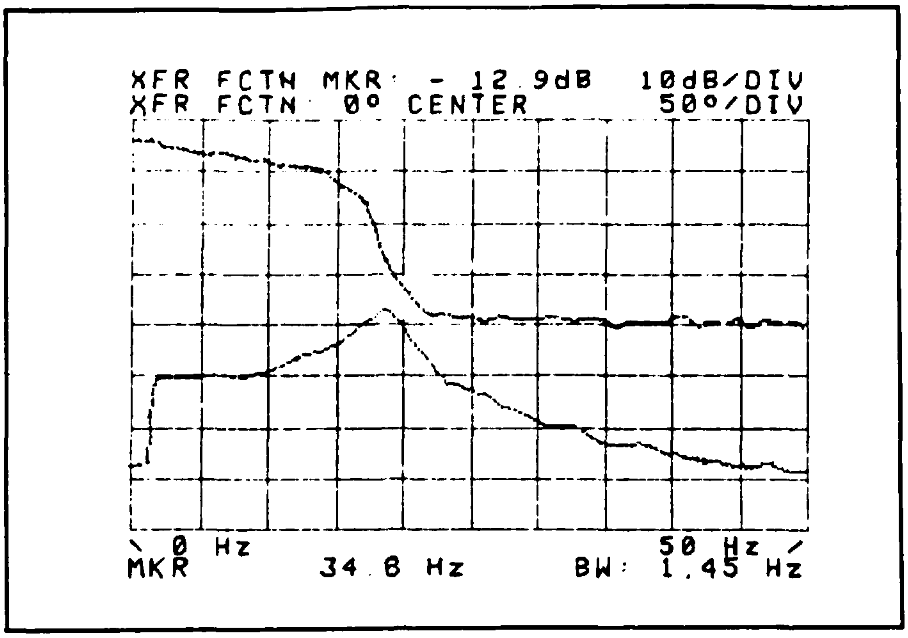

Figure B. Spectrum Analyzer Closed Loop Output

Step 3: The closed loop response was transferred to a Nichol's chart, the open loop response obtained and plotted on a Bode diagram. Using asymptotes the open loop transfer function can be written as:

$$G_{ol}(s) = \frac{165}{s\left(\frac{s}{66} + 1\right)}$$

<u>Open Loop Transfer Function</u>: The open loop frequency response was measured by connecting the channel A input of the spectrum analyzer to the forward path at T19, see Figure D.

Data points of phase and magnitude from the spectrum analyzer output were tabulated and plotted on a Bode Diagram, Figure E.

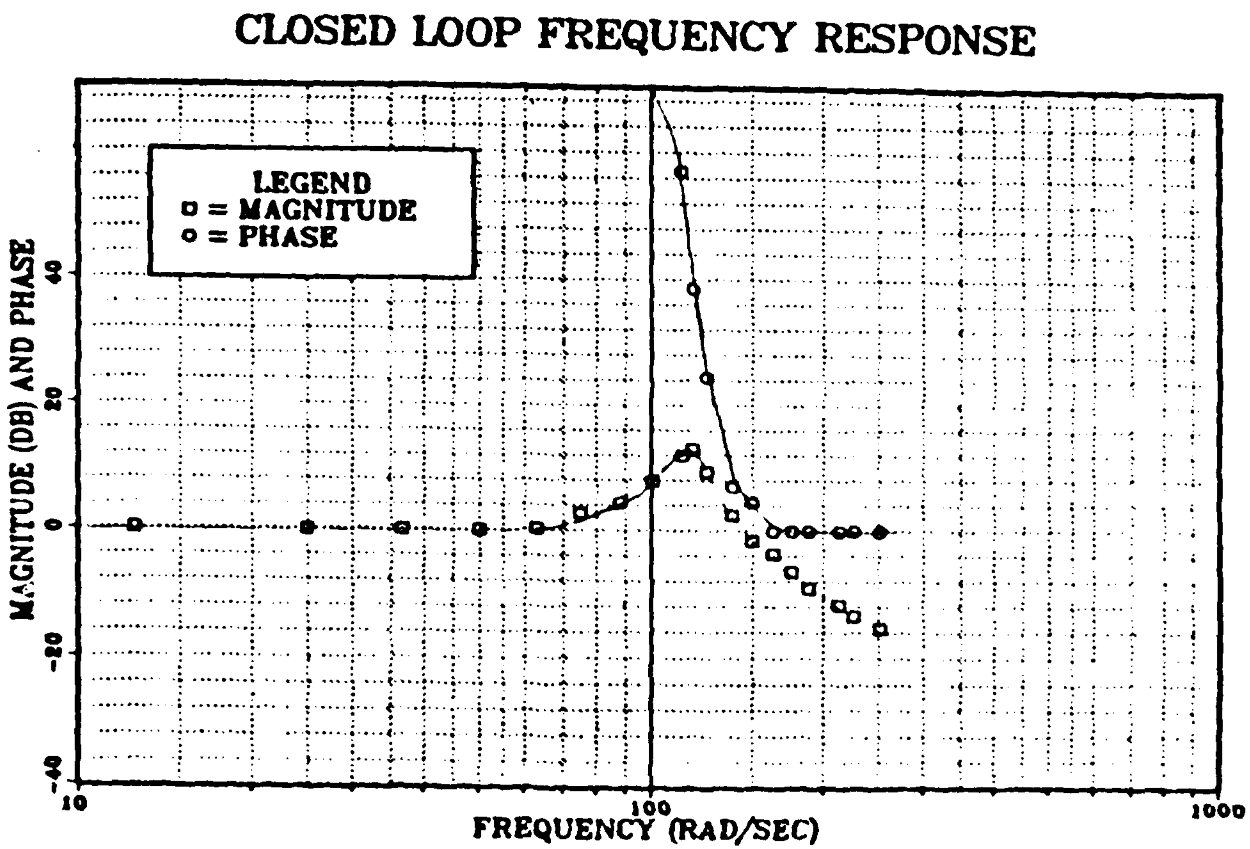

Figure C. Spectrum Analyzer Closed Loop Data

The resulting transfer function determined by fitting asymptotes to the data can be written as:

$$G_{ol}(s) = \frac{165}{s\left(\frac{s}{55}+1\right)\left(\frac{s}{350}+1\right)}$$

Where the open loop gain from the closed loop method was used to obtain the low frequency portion of the curve. This assumption for gain was possible because the -40 db/dec asymptotes of both plots crossed the 100 rad/sec frequency at 0 db.

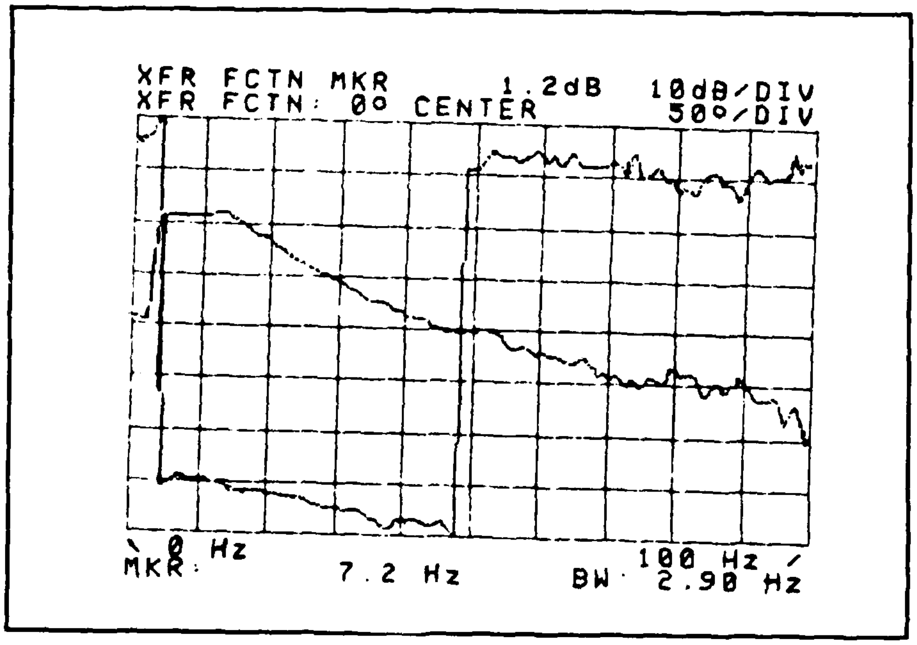

Figure D. Spectrum Analyzer Open Loop Output

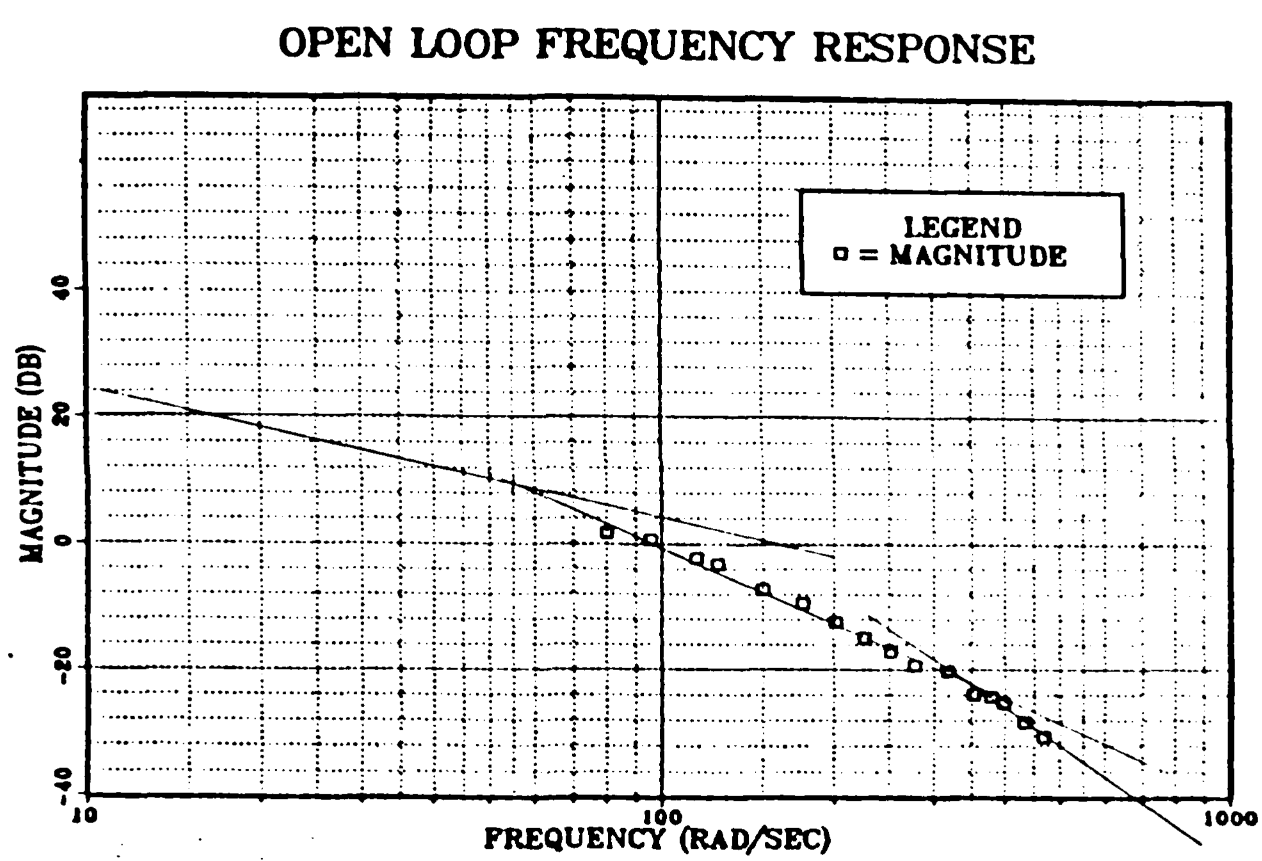

Figure E. Spectrum Analyzer Open Loop Data

CONCLUSIONS:

The affect of forward gain on the system stability acted as would be expected in a closed loop position control second order system. As the gain is increased the real part of the complex roots of the characteristic equation become positive causing the instability condition.

The open loop transfer functions obtain by the two methods agree closely. Because of the limited bandwidth of the closed loop system the additional pole was not found from the data of Figure A.

* Block Diagram of system test equipment connections omitted.

RECOMMENDATIONS AND COMMENTS: * Student comments.

LABORATORY IV B REPORT

TITLE: CLOSED LOOP POSITION CONTROL - VELOCITY DAMPING

PURPOSE: Measure the effect of adding velocity feedback damping to a position control system and how the response varies with respect to forward and feedback gain.

DISCUSSION: The system is set up in the position control mode of operation as in Lab IV A and a variable attenuation velocity feedback voltage is also fed back to damp the system.

RESULTS:

Position Control with Velocity Feedback

Step 3: A 50% attenuated velocity feedback signal was added to the summer, and forward gain raised to HIGH-MIN to determine the effect of an external load. The motor shaft could be moved only slightly, indicating any error from load variations was small.

Step 5: A chart recorder was used to record the variation in step response of the system as forward gain and velocity feedback attenuation were varied. The results are shown in the attached figures. * Four of the recorder results are shown in Figures A - D.

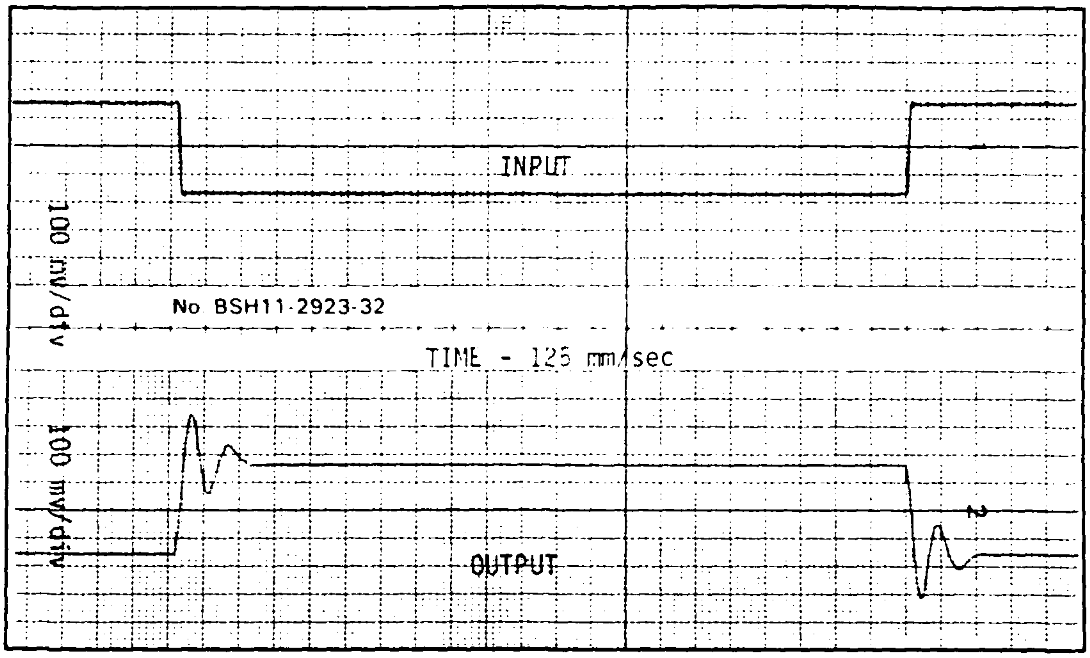

Figure A Closed Loop Step Response - Gain Settings LOW 1/2 - FULL

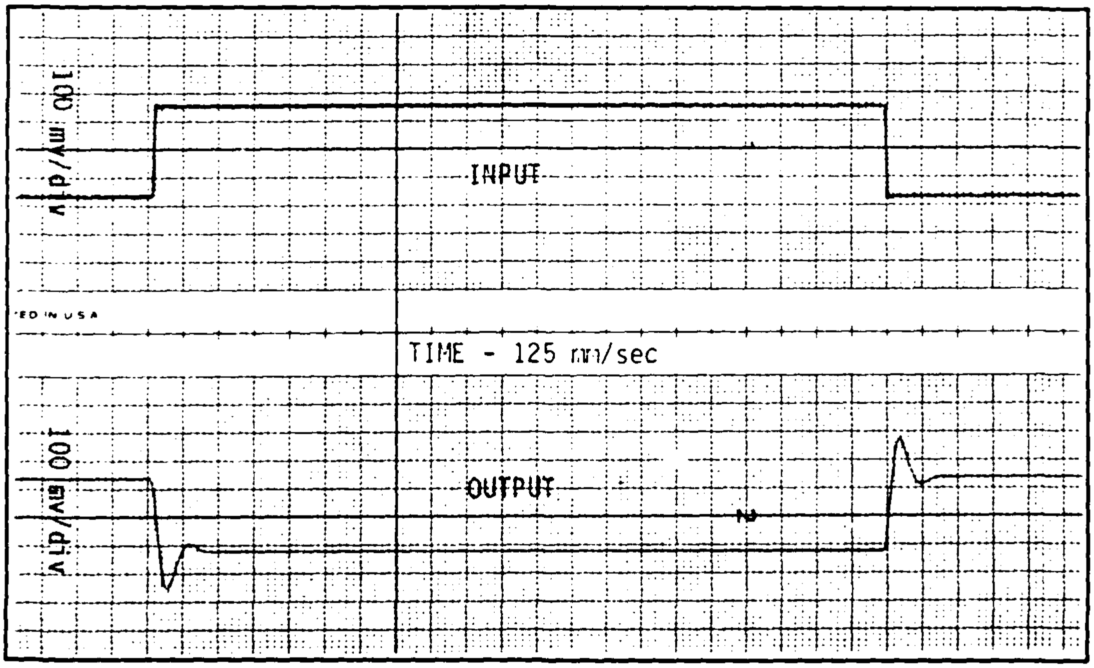

Figure B Closed Loop Step Response - Gain Settings LOW 1/2 - 1/2

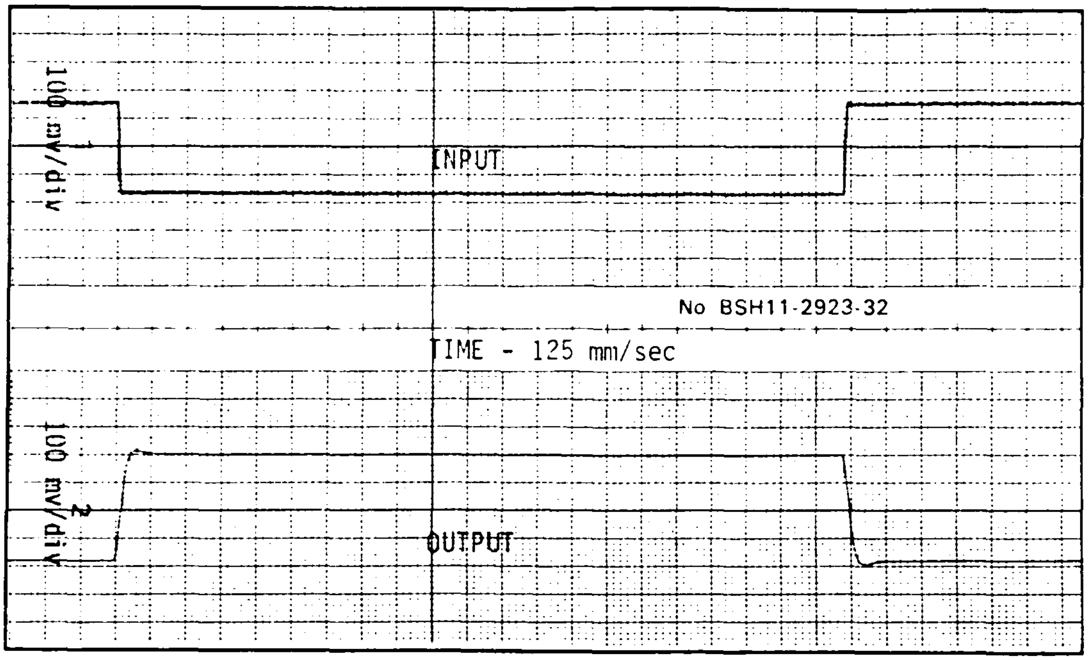

Figure C Closed Loop Step Response - Gain Settings LOW 1/2 - 0

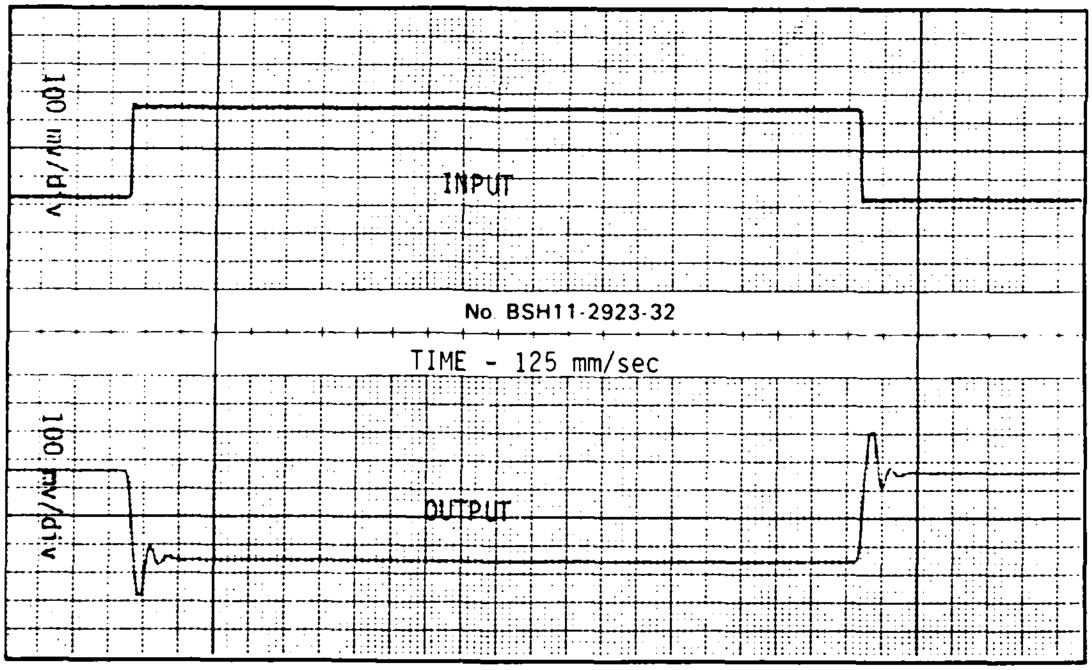

Figure D Closed Loop Step Response - Gain Settings HIGH/MIN - FULL

CONCLUSIONS:

1. The chart records were analyzed to determine the relationships between gain variations and response characteristics with the following results:

Rise time and time constant - For a constant damping setting the rise time and time constant decrease for increases in forward gain. This is expected from the calculations in Lab III A. When forward gain is held constant and damping varied, the rise time and time constant are not significantly changed.

Stability - The system remained stable for all variations in gain and damping. The amount of overshoot and number of oscillations did not vary significantly for changes in gain, but decrease with increase in the damping. The damping was adjusted to the point where no oscillation or overshoot occurred, this corresponds to a damping ratio ξ of 0.707 in a second order system.

Settling time - This varied with both gain and damping. As gain is increased and damping is increased (less attenuation) the settling time was reduced.

RECOMMENDATIONS AND COMMENTS: *Student comments.

APPENDIX F

LINEAR CONTROL PROJECTS

1. <u>Cascade Compensation</u>

Using the open loop transfer function obtain in the basic labs, design a cascade compensator to stabilize a closed loop position system with high gain. Test your design by simulation, construct the filter, test in the hardware, and compare results.

2. <u>Mechanical Resonance</u>

Determine the effect of a springy shaft between the motor and position sensor. Install rubber tubing between the motor and position sensor. Determine the resonant frequency and adjust the notch filter to reduce the resonance.

3. <u>Bang - Bang Control</u>

Design a relay circuit with the output shown in Figure F.1, install in the forward path and study the behavior of the system.

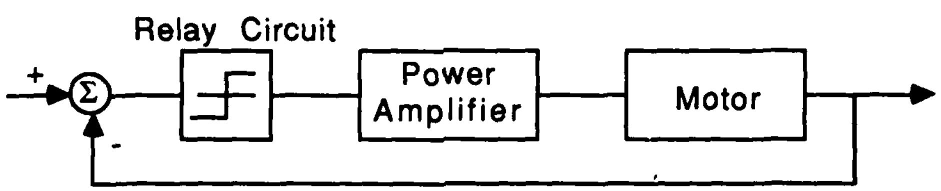

Figure F.1 Bang - Bang Control

DIGITAL CONTROL PROJECTS

1. Sampled Data System - No Hold

Design an analog discrete sampler with no hold. Install in the forward path (at external cascade compensation point) and study the effect of the sampling rate on system stability and response in a closed loop position control mode.

2. Sampled Data System - Zero Order Hold

Design an analog discrete sampler with a zero order hold. Install in the forward path (at external cascade compensation point) and study the effect of the sampling rate on system stability and response in a closed loop position control mode.

3. Analog to Digital (A/D) Sampled Data System

a. Design an analog to digital and digital to analog sampling circuit with zero order hold, place in cascade and determine the effect of sampling rate and discuss how bit length (sensitivity) of the A to D converter may effect the system.

b. Place the A to D and D to A circuit in the position feedback path. Measure its effect on the system.

c. Using analog position feedback, place the A to D and D to A circuit in the velocity feedback damping path and determine how the sampling rate effects system damping.

4. Digital Shaft Encoder

Install a digital shaft encoder on the motor shaft. Design an up/down counter circuit with an digital to analog converter to produce an analog position signal. Measure the effect of the encoder on system performance.

5. Digitally Compensated Sampled Data System

Design a circuit as shown in Figure F.2, with the microprocessor programmed with a digital filter cascade compensation algorithm. Study the effects of digital control on system performance.

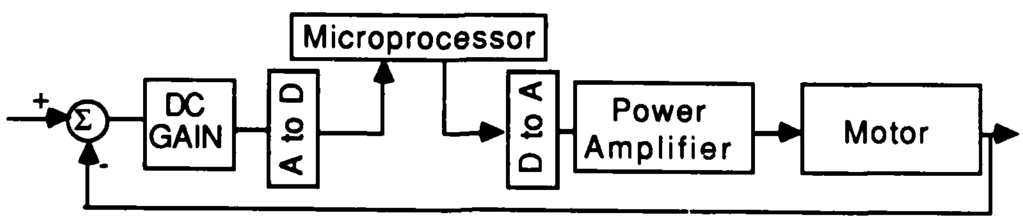

Figure F.2 Microprocessor Compensation

LIST OF REFERENCES

1. Electro-Craft Corporation, DC Motors Speed Controls Servo Systems, 2nd ed., October 1973.

2. Electro-Craft Corporation Robbin Myers Division, Motomatic Speed & Position Control Systems, catalogue, 1986.

3. IBM Corporation, Dynamic Simulation Language/VS Language Reference Manual, 1st ed., June 1984.

4. Electro-Craft Corporation, LA-5600 Linear Amplifier Instruction Manual, doc no. 7058-9954-031, June 1986.

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